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Tropospheric Passive Remote Sensing

Proceedings of a workshop held in Virginia Beach, Virginia July 20-23, 1981

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Tropospheric Passive Remote Sensing

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Proceedings of a workshop sponsored by the NASA Office of Space Science and Applications and the NASA Office of Aeronautics and Space Technology, conducted by Langley Research Center, and held in Virginia Beach, Virginia
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PREFACE

The Tropospheric Passive Remote Sensing Workshop, sponsored jointly by the NASA Office of Space Science and Applications and Office Aeronautics and Space Technology, was held in Virginia Beach, Virginia, July 20-23, 1981. The purpose of the workshop was to define the long-range role of passive remote sensors in tropospheric research and identify the technology advances necessary to implement that prescribed role.

Approximately 20 scientists and technologists were selected to participate in the workshop. Assignments were made to either the Sensor Systems Panel or the Sensing Technology Panel for the purpose of deliberating on the role of passive sensors or on the necessary technology advances, respectively. The interests and activities of each panel overlapped, and several combined sessions were held, so that the final recommendations reported herein represent a consensus of all participants.

A number of presentations by workshop members and invited speakers reviewed measurements to date as well as the developmental status of various sensing techniques and relevant technologies. These presentations also served to initiate technical interchange among workshop members. Pertinent inputs to the workshop (e.g., presentation material and certain supporting and complementary material) are incorporated in a synopsized form in this publication in order to highlight the workshop conclusions and recommendations.

Special thanks are extended to Dr. Allario for suggesting the workshop, Drs. Murcray and Kingston for serving as panel chairmen, Drs. Logan and Danielsen for serving as measurement requirements rapporteurs from an earlier meeting, Mr. Hoell and Mr. Dodgen for serving as panel recorders, and Mr. Curfman (and other Bionetics Corp. personnel) for serving as technical consultant and logistics coordinator.

Lloyd S. Keafer, Jr., and Henry G. Reichle, Jr.
Workshop Cochairmen

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EXECUTIVE SUMMARY

The Tropospheric Passive Remote Sensing Workshop met July 20-23, 1981, to address two objectives. The first was to identify the long-term role of passive remote sensing systems on spacecraft and aircraft to support the measurement and mission needs of the NASA Tropospheric Air Quality Program. The second was to identify the long-term sensing technology advances required to enhance the performance of those passive systems deemed most promising for future tropospheric research and operational use.

Two rapporteurs supported the workshop, which was organized into two panels, the Sensor Systems Panel and the Sensing Technology Panel. The rapporteurs presented the measurement and mission needs from two viewpoints: that of the atmospheric chemist, concerned with the trace gases and aerosols of importance, and that of the meteorologist, concerned with the transport phenomena which must be understood to interpret the measurements made of any of the species. The Sensor Systems Panel assessed the relative merits of various sensor systems in responding to the identified measurement and mission needs and noted the role of specific passive remote sensors in the tropospheric research program. The Sensing Technology Panel responded by identifying technology development thrusts needed for the various systems recommended. Reviews of the generic sensor types and of the status of the required technology elements supported the activities of the two panels.

It was concluded that passive remote sensing techniques have a meaningful and challenging role in addressing the measurement needs of the tropospheric research program. Spectral survey and species-specific sensors using both nadir- and limb-viewing techniques were identified for providing multilayer measurements in the troposphere. The value of spectra measured by spectral survey instruments was particularly emphasized for tropospheric research tasks. Since limb-viewing sensors have a rich science and technology heritage from the stratospheric program and can probably be applied without new technology, technology thrusts were focused on nadir-viewing systems.

SENSOR SYSTEMS PANEL RECOMMENDATIONS

The conclusions and specific recommendations, from a systems point of view, for passive remote sensing of tropospheric constituents were as follows:

- Passive remote sensing systems exhibit promise and should be developed for measurement of the more abundant tropospheric trace species.
- Nadir-viewing and solar occultation should be considered in combination for tropospheric measurements of those gases having large stratospheric burdens.
- A nadir-viewing instrument capable of obtaining continuous spectra in several bands in the 3- to 15-μm region with a spectral resolution of at least 0.1 cm^{-1} is desired for the long term.
- Gas filter radiometers for species-specific measurements should continue to be developed concurrently with a spectral survey instrument, especially in the short term.

- Further development of aerosol retrieval algorithms, including polarization techniques, is required for obtaining aerosol thickness and size distributions and, possibly, refractive indexes.

- Investigations should be conducted, including the use of existing spectral scanning and gas filter instruments, to study (1) the effects of instrument noise and background fluctuations on inversion techniques, (2) the ability to obtain gas profiles (at least two layers) in the troposphere, (3) the accuracy requirements on all parameters required for species determination, and (4) the extent to which solar scattering can be used to obtain lower-level tropospheric data.

SENSING TECHNOLOGY PANEL RECOMMENDATIONS

Because of the particular interest in broadband spectrometry and gas filter radiometry, the Sensing Technology Panel identified specific technology thrusts for these approaches as follows:

Broadband Spectrometers

All types: Onboard "smart" processing

Cryogenics/cooling

Grating types: 1000-element arrays

Large gratings

Interferometers: Mitigation of background fluctuations

Multiaperture, multiband interferometers

In-flight alignment verification

Gas Filter Radiometers

Gas filter cell technology

Linear and high-dynamic-range detectors

Highly uniform optical elements

Certain technology thrusts were identified as necessary regardless of the sensing systems chosen for tropospheric research. In response to the need for more accurate measurements over long periods of time, resulting in greater volumes of data, the following thrusts were recommended: detector arrays, cryogenic cooling (of sensors and optics), sophisticated optical elements, data processing as an integral part of the sensor, and calibration techniques and equipment.

INTRODUCTION

A workshop on Tropospheric Passive Remote Sensing was held in Virginia Beach, Virginia, on July 20-23, 1981. One of the sponsors was the National Aeronautics and Space Administration Office of Space and Terrestrial Applications, now the Office of Space Science and Applications (OSSA), which is responsible for NASA's Tropospheric Air Quality Program. The Tropospheric Air Quality Program, alternately referred to as the Tropospheric Research Program, is one of several applications programs conducted by NASA which are directed toward relevant national needs. The long-term objective of the program is to apply NASA's space technology to assess and predict human impact on the troposphere, particularly on the regional to global scale where the synoptic view afforded by satellites and the increasing importance of pollution on these scales suggest that space observations can play a unique and critical role.

The troposphere is that region of the atmosphere in which man has long studied and observed the weather. The chemistry of the troposphere, especially as influenced by man through the introduction of trace gases (some of which are called pollutants), is poorly understood at the present time, particularly on the large regional or global scales. The OSSA recently sponsored a working group from the scientific community to provide an overview of the scientific problems that need to be addressed in order to understand the large-scale troposphere. Their findings are published as the Report of the NASA Working Group on Tropospheric Program Planning (Seinfeld et al., 1981). The major thrust of the NASA Air Quality Program is the implementation of a broad research effort responding to the scientific recommendations of this working group. The development of the necessary scientific understanding of the troposphere requires a broad program with four components: instrument development, mathematical modeling, and laboratory and field measurement activities. Both passive and active remote sensing flight experiments are included in the program. At the time of this workshop the Measurement of Air Pollution from Satellites (MAPS) passive sensor was being readied for flight aboard STS 2. This November 1981 flight was the first in a planned series of four experiments continuing through 1984. NASA desires to capitalize on the MAPS sensor development and flight experiments to provide greater scientific return from similar and more advanced passive sensors. Therefore, OSSA's question for the workshop was: "With the inherent advantages that passive sensors have regarding cost, simplicity, weight, power and reliability, what is their long-range role in tropospheric research?"

The other sponsor of the workshop was the NASA Office of Aeronautics and Space Technology (OAST), which is responsible for developing critical technologies to enable or enhance the performance of a wide variety of potential NASA missions. Since technology advancements evolve from many disciplines, the OAST maintains a close liaison and cooperation with other government agencies, especially the Department of Defense, as well as with the aerospace industry for those technology elements relevant to NASA missions. The OAST remote sensing technology program includes fundamental electronics research, sensor component and device development, system and subsystem development of high-technology sensors, and development of sensor support systems such as cryogenic coolers, scanning mechanisms, pointing devices, and information systems. Therefore, OAST's question for this workshop was: "What new technologies are needed in any of these areas to implement fully the role prescribed for passive remote sensors in the Tropospheric Research Program?"

With these two NASA offices, the Office of Space Science and Applications and the Office of Aeronautics and Space Technology, as sponsors, the NASA Langley Research Center was assigned the task of organizing and conducting this Tropospheric Passive Remote Sensing Workshop.

OBJECTIVES AND ORGANIZATION

In direct response to OSSA and OAST needs, two objectives were established for the workshop:

(1) To identify the long-range role of passive remote sensing systems on spacecraft and aircraft to support the measurements and mission needs of the Tropospheric Air Quality Program

(2) To identify the long-term sensing technology required to enable and enhance the performance of passive remote sensor systems for tropospheric research and operational use

The restrictions included in these objective statements were intentional. Active remote sensing systems (e.g., lidar and radar) were not considered, nor were trade-offs between active and passive methodologies for meeting the measurement needs. Similarly, the technology of concern was that which relates primarily to the implementation of passive or radiometric instrumentation. Spacecraft and aircraft are the primary platforms for passive remote sensors. Sensors utilizing ground-based platforms may meet some specific needs, but are generally not practical for measurements on large regional and global scales. Long-range or long-term implies going beyond the runout of current flight measurement plans and allowing sufficient time for development of new technologies. This means that the time scale for implementing the long-range role is the decade of the 1990's, but the time period for technology developments includes the 1980's. The development of "enabling" technology commands a high priority, but in an era when affordability is a prime criterion for selection of flight experiments, any technology item that enhances or maintains performance at reduced cost is important. Often these may be the sensor support or operational items rather than the sensing elements per se. Although trade-offs between active and passive systems were not considered, the inherent advantages of passive sensors in cost, simplicity, weight, power, and reliability were not ignored in meeting the stated workshop objectives.

The workshop organization and the key participants are listed as follows:

Workshop Cochairmen

Lloyd S. Keafer, Jr., and Henry G. Reichle, Jr.

Measurement and Mission Needs Rapporteurs

Jennifer A. Logan and Edwin F. Danielsen

Sensor Systems Panel

David G. Murcray, Chairman
Michael Griggs
Wilfred D. Hesketh
E. David Hinkley
James M. Hoell, Jr.
John A. Reagan
Laurence Rothman
Harold Zwick

Sensing Technology Panel

Robert H. Kingston, Chairman
Frank Allario
John A. Dodgen
Edward J. Hurley
John A. Jamieson
A. Fenner Milton
David D. Norris

The participants, primarily from universities and government, were selected because of their personal knowledge of and experience with passive remote sensing measurements, systems, and technologies, as well as because of their awareness of the status of industry's developments and applications relevant to passive remote sensing. A listing of all workshop participants and their affiliations is given in Appendix A.

Although the workshop responded directly to NASA program needs, the selected participants included non-NASA atmospheric scientists, measurement specialists, and instrument technologists, and the workshop results should also serve their needs and those of their government, industry, and university colleagues.

Two rapporteurs served the workshop through presentations which identified measurement and mission needs for the troposphere. Both of the rapporteurs had participated in an earlier meeting of a Working Group on the Application of Modeling Research Results to the Design of a Global Tropospheric Experiment (National Aeronautics and Space Administration, 1982). The Sensor Systems Panel was charged with assessing the relative merits of various sensor systems in response to the identified measurements and mission needs and identifying the future role of passive remote sensors in the Tropospheric Research Program (objective 1). The Sensing Technology Panel had the responsibility of responding to the Sensor Systems Panel by identifying technology development thrusts needed for the various recommended systems (objective 2).

Several activities supported the panels prior to their detailed discussions and responses. Before the meeting each participant was asked to respond to several questions, and the responses of each were made available to the other participants. The questions and results of this preworkshop effort are presented in Appendix B. A series of Generic Sensor Reviews was also presented to the workshop prior to the panel sessions. These topics and presenters were as follows:

Absorption and Emission Spectroscopy	David G. Murcray
Correlation Spectrometry	Harold Zwick
Gas Filter Radiometry	Wilfred D. Hesketh
Radiometry for Aerosols	Michael Griggs
Heterodyne Sensing	E. David Hinkley
Stratospheric Sensing Experience	James Russell
Off-Nadir Sensing Considerations	Fred Alyea

Further, the Sensing Technology Panel conducted its own reviews of pertinent technology elements. These topics and presenters were as follows:

Array Detectors	A. Fenner Milton
Imaging Spectrometer Technology	David D. Norris
Smart Sensors	Roger A. Breckenridge
Optics and Filters	Edward J. Hurley
Radiometric Calibration	John A. Dodgen

These review papers are not included herein; however, pertinent references for each of these topics are contained in Appendix C. Listed in Appendix D are the acronyms and abbreviations used in this document. The remainder of this report contains the principal workshop products in the form of rapporteur reports, panel reports, and a summary of workshop recommendations. These workshop results are also reported in a short preliminary paper presented at the 1982 AIAA Aerospace Sciences Conference (Keafer and Reichle, 1982).

MEASUREMENT AND MISSION NEEDS

The following quote from the Report on the NASA Working Group on Tropospheric Program Planning (Seinfeld et al., 1981) aptly describes the fundamental goal of the research program.

> The state of the troposphere impacts on a number of areas of concern to man and the environment, including health, weather, climate, and agriculture. The troposphere consists of a large number of chemical species, some long-lived, such as oxygen, nitrogen, and carbon dioxide, and some of an extremely transient nature that are rapidly formed and destroyed by chemical reactions. In general, the chemical transformations that occur interrelate the individual biogeochemical cycles of carbon, nitrogen, sulfur, etc. through these transient species. The transient, or trace, species exert a disproportionate leverage on tropospheric chemistry over what might be expected on the basis of their absolute concentrations. They may influence visibility by conversion to light-scattering and absorbing aerosols, climate through their effects on the radiation balance, or the ecosystem through effects such as acid-rain formation. Understanding the distribution, sources, sinks, and variabilities of the minor and trace species in the troposphere is a fundamental goal of the NASA Air Quality Program.

To determine what this means in terms of measurements and missions is a task that was undertaken by the Working Group on the Application of Modeling Results to the Design of a Global Tropospheric Experiment (National Aeronautics and Space Administration, 1982), which met just prior to this workshop. Two rapporteurs from that meeting served the workshop by identifying measurement needs regarding a number of chemical and transport parameters which may be wholly or partially met by missions employing passive remote sensors. Dr. Logan discussed the chemistry needs and Dr. Danielsen discussed the transport needs with the workshop.

CHEMISTRY

Introduction

A long-range goal of the working group which met prior to this workshop is to determine the processes which control the composition of the troposphere and to assess the extent to which man's activities might be perturbing its composition. Attainment of this goal will involve measurement of the global distribution of those gases involved in tropospheric photochemistry (e.g., O_3, CO, CH_4, NO_x) and quantification of their sources and sinks, in addition to a fundamental understanding of atmospheric transport processes and chemical transformations. If we had a snapshot of the distribution of certain gases in the troposphere, especially those gases whose lifetimes are longer than a few days, we might learn a great deal about the sources of those gases. This kind of information is sorely lacking at the present time. We hear a great deal about tropospheric OH and it is very timely that this workshop is being held exactly 10 years after Levy (1971) first postulated the existence of OH in the troposphere and its role as a major sink for many tropospheric gases. Before discussing some of the gases that might be measured by remote sensing, a review of tropospheric chemistry is presented to explain why these gases are important and to assess the impact of measurements of several trace gases on the knowledge of their sources and sinks. (Much of the material herein is discussed in more detail in Logan et al. (1981).)

Background

Listed in table 1 are a number of gases which are removed from the troposphere by reaction with OH. Many of these gases, for example, carbon monoxide and many hydrocarbons and halocarbons, have anthropogenic sources. Reaction with OH converts NO_2 to nitric acid, and OH plays an important role in converting SO_2 to sulfuric acid. OH is really a key player in all of tropospheric photochemistry. Hydroxyl is produced by the photolysis of ozone followed by the reaction of $O(^1D)$ with water, and is destroyed in the atmosphere by reaction with CO and methane. (See fig. 1). Clearly, the distributions of at least four gases, ozone, water vapor, CO, and methane, are required to model the chemistry of OH. The concentration of OH depends also on the concentration of NO. Odd-hydrogen species (H, OH, HO_2) may be interconverted by reactions involving NO and O_3. Hydroxyl is regenerated by the reaction of HO_2 with NO, and the amount of OH at any location depends critically on the amount of NO. Figure 2 shows how the concentration of OH depends on the mixing ratio of NO over the range of concentrations found in the troposphere. Nitric oxide concentration varies between a few parts per trillion and hundreds of parts per billion.

TABLE 1. OH PHOTOCHEMISTRY

Reaction with OH is the major sink for:

CO	CH_3Cl	H_2S
CH_4	CH_3Br	CS_2
C_xH_y	CH_3CCl_3	Reduced S species
H_2	Halocarbons	

Critical OH reactions:

$$OH + NO_2 \xrightarrow{M} HNO_3$$

$$OH + SO_2 \xrightarrow{M} HSO_3 \rightarrow H_2SO_4$$

Source:

$$O_3 + h\nu \rightarrow O(^1D) + O_2$$

$$O(^1D) + H_2O \rightarrow OH + OH$$

Sinks:

$$OH + CO \rightarrow CO_2 + H$$

$$OH + CH_4 \rightarrow CH_3 + H_2O$$

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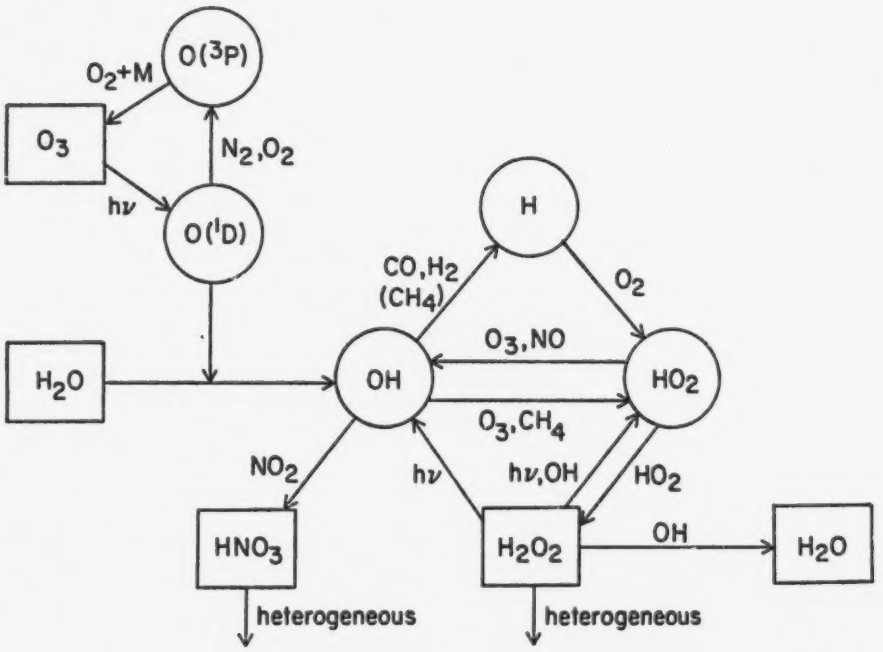

Figure 1.- Chemistry of odd-hydrogen species. (From Logan et al., 1981.)

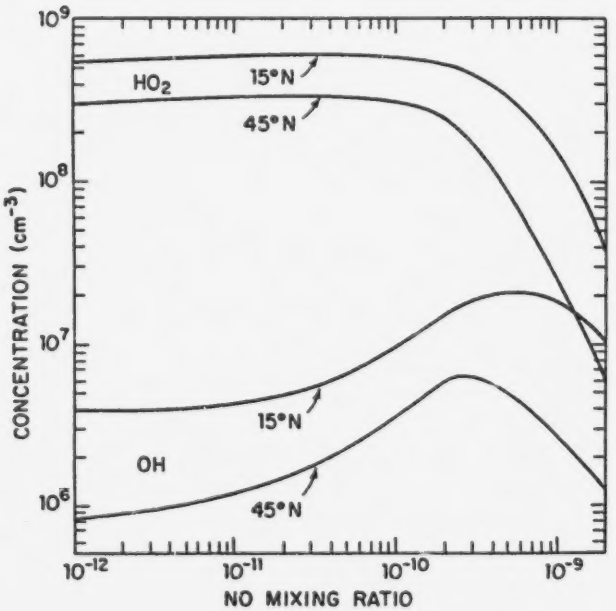

Figure 2.- OH dependence on NO mixing ratio. (From Logan et al., 1981.)

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Nitric oxide is also implicated in the photochemistry of ozone in the troposphere. Until a few years ago, it was thought that the concentration of ozone in the troposphere was controlled mainly by dynamic processes. Ozone was transported from its source region in the stratosphere to the troposphere and was then destroyed by heterogeneous processes at the Earth's surface. It now appears that photochemistry also plays an important role in determining the distribution of ozone in the troposphere. For example, ozone may be generated in the troposphere by the oxidation of carbon monoxide (table 2). The key step in this process is the reaction of HO_2 with NO. HO_2 also reacts with ozone and provides a sink for it. There is competition between these two reactions of HO_2, one of which generates ozone and the other which destroys it. The net photochemical production of ozone depends critically on the amount of NO in the troposphere.

TABLE 2. O_3 PHOTOCHEMISTRY

Photochemical production of odd oxygen
(1) $OH + CO \rightarrow CO_2 + H$
$H + O_2 + M \rightarrow HO_2 + M$
$HO_2 + NO \rightarrow OH + NO_2$
$NO_2 + h\nu \rightarrow NO + O$
$O + O_2 + M \rightarrow O_3 + M$
$h\nu + CO + 2O_2 \rightarrow CO_2 + O_3$
(2) $CH_3OO + NO \rightarrow CH_3O + NO_2$
or
$RO_2 + NO \rightarrow RO + NO_2$

Photochemical sinks for ozone
(1) $O_3 + h\nu \rightarrow O(^1D) + H_2O$
$O(^1D) + H_2O \rightarrow OH + OH$
(2) $HO_2 + O_3 \rightarrow OH + 2O_2$
(3) $OH + O_3 \rightarrow HO_2 + O_2$

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Ozone may also be produced in the photooxidation of methane. The chemistry of ozone in the troposphere is illustrated in figure 3. Current models suggest that photochemical production and destruction of ozone are in balance for concentrations of NO of about 30 pptv. Tropospheric photochemistry is a very tightly coupled system; i.e., the same reactions are important in the chemistry of odd hydrogen, odd oxygen, and odd nitrogen. If we wish to understand the photochemistry that controls the concentrations of OH and ozone, we need measurements of the distributions of NO and of the longer lived trace gases like water vapor, carbon monoxide, methane, and ozone. The rest of this section will focus on current knowledge of the distributions of these gases and will discuss what might be learned about their sources from improved measurements of their distributions.

Discussion

The composition of the atmosphere, in order of abundance, is summarized in table 3. Some information is also given about the status of measurements of different gases. H_2O, CH_4, CO, O_3, and NO_x will be discussed at this point without regard for whether or not they can be measured by remote sensing.

Water vapor.- A great deal of data is available for the distribution of water vapor in the troposphere, primarily from the radiosonde network. Oort and Rasmussen (1971) have analyzed data from the radiosonde network and give mean values for water vapor as a function of latitude, altitude, and season. The major gap in the data base for water vapor is the lack of reliable data for the upper troposphere above 5 km. Mastenbrook (1966, 1968) has made the most extensive set of measurements of H_2O in the upper troposphere, and some typical profiles are given in figure 4. The concentration of water vapor is very variable in the troposphere and it would be useful to have more measurements of its distribution above 5 km.

Methane.- Methane is present in the troposphere at a concentration of about 1.7 ppmv. It is uniformly distributed, as would be expected from its rather long lifetime (~8 years). It is destroyed by reaction with OH. There have been a few measurements of the latitudinal distribution of methane and several measurements of its distribution as a function of altitude. There is slightly more CH_4 in the Northern Hemisphere than in the Southern Hemisphere. Some shipboard measurements of CH_4 near Indonesia show higher concentrations than are found elsewhere. This might be indicative of local source regions.

There has recently been a resurgence of interest in the methane budget because there are indications that the concentration might be increasing. Measurements suggest that the concentration of CH_4 has increased by approximately 2 percent per year over the past 3 to 4 years (Rasmussen and Khalil, 1981). It is more difficult to say whether there is a trend evident in the data from 1968 to 1975 because there is a great deal of variability in the earlier measurements. There are also spectroscopic measurements of the total column of methane. It might be possible to analyze these data for a historical trend, but this has not been done.

The sources of methane are listed in table 4. Clearly the sources are rather hard to quantify. Methane is produced in highly reducing environments such as paddy fields and marshes, and by enteric fermentation in animals. Current measurements do not show much variability in the concentration of methane, but a global snapshot of its distribution might provide some information on source regions. It is important to learn whether methane is increasing, and, if it is, whether the increase is due to a change in sources or sink.

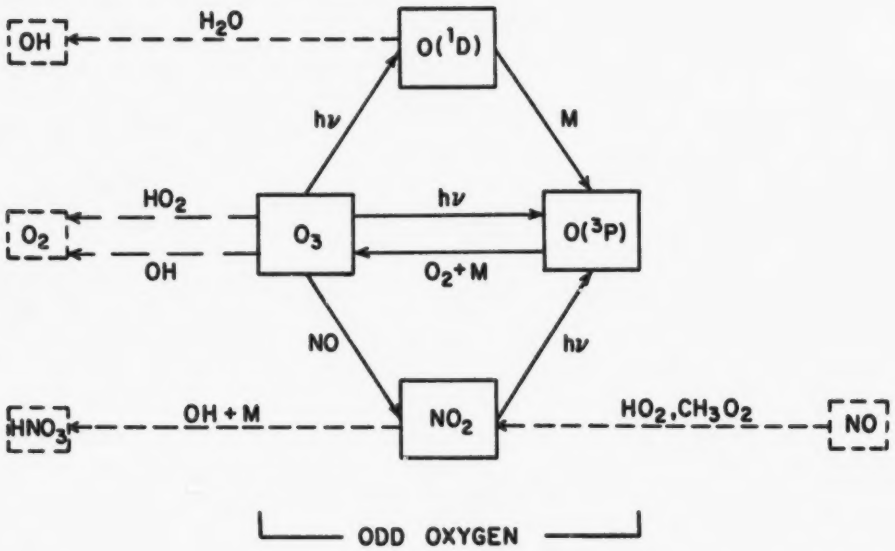

Figure 3.- Chemistry of odd-oxygen species. (From Logan et al., 1981.)

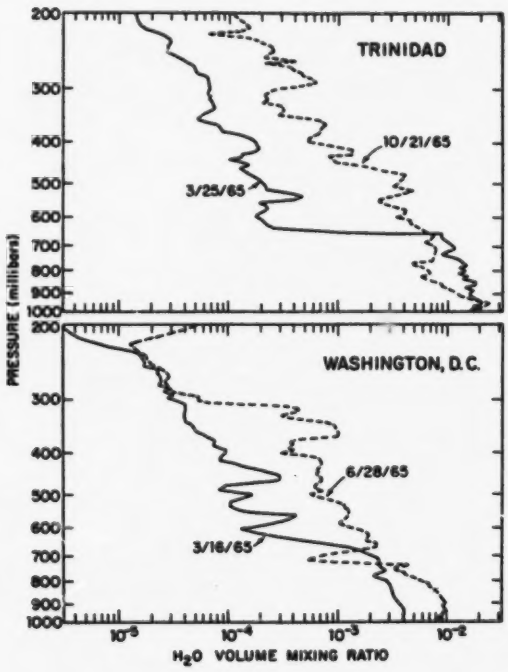

Figure 4.- Typical water vapor profiles. (From Logan et al. (1981) based on data of Mastenbrook (1966, 1968).)

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TABLE 3. ATMOSPHERIC COMPOSITION

Constituent	Fractional abundance	Trend	Seasonal	Latitudinal	Altitude	Local
N_2	7.8×10^{-1}					
O_2	2.1×10^{-1}					
Ar	9.3×10^{-3}					
H_2O	$10^{-3} - 10^{-2}$		✓	✓	✓	
CO_2	3.3×10^{-4}	a	✓	✓	✓	*
CH_4	1.6×10^{-6}			✓	✓	*
H_2	5×10^{-7}			✓	✓	*
N_2O	3×10^{-7}		✓	✓	✓	✓
CO	$\sim 10^{-7}$		✓	✓	*	*
O_3	$10^{-8} - 10^{-7}$		✓	✓	✓	b
NO_2, NO	$10^{-11} - 10^{-8}$					*
H_2O_2	$\sim 10^{-10}$					
HO_2	$\sim 10^{-12}$					
OH	$\sim 10^{-14}$					*
$O(^1D)$	$\sim 10^{-23}$					

✓ Reasonable data base.
* Fragmentary data.
a Data available since 1958.
b Northern Hemisphere.

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TABLE 4. CH_4 BUDGET (from Ehhalt and Schmidt, 1978)

Sources (10^{12} g yr^{-1})	
Enteric fermentation of animals	100 - 200
Paddy fields	~280
Swamps, marshes	190 - 300
Total	570 - 780

Sink (10^{12} g yr^{-1})	
Reaction with OH	300 - 600

Carbon monoxide.- Measurements of carbon monoxide are summarized in figure 5. Most of these measurements were made by Seiler and coworkers (Seiler, 1974; Seiler and Schmidt, 1974); the cross-hatched area at the left shows measurements made by Heidt et al. (1980) on the GAMETAG project. During GAMETAG, a flight measurement program funded by the NSF, an instrumented aircraft was flown over the North American continent from 50°N to 30°N and over the Pacific Ocean from 30°N to 60°S, making measurements of as many atmospheric constituents as possible with current technology. With the exception of the GAMETAG data and one flight on the west coast of North and South America, all measurements shown in figure 5 were taken over the Atlantic Ocean. The concentration of carbon monoxide varies from about 50 ppbv in the Southern Hemisphere to over 200 ppbv at northern midlatitudes. The north-south gradient is smaller in the upper troposphere than in the boundary layer. The boundary layer measurements indicate that the concentration is much more variable in the Northern Hemisphere than in the Southern Hemisphere.

Some representative profiles of carbon monoxide, taken from a recent paper by Seiler and Fishman (1981), are shown in figure 6. One striking feature of these profiles is the uniform distribution of CO in the Southern Hemisphere, south of ~40°S. While the gross features of the CO distribution are known from latitude surveys, there is considerable uncertainty in our knowledge of important aspects of the distribution of the gas. For example, the seasonal variation is not defined. The range in concentration measured in the Southern Hemisphere may be due in part to seasonal variations, or it may reflect differences in calibration between various research groups. The only measurements of the seasonal variation are from two stations that have been established by Seiler on Mauna Loa, Hawaii, and in South Africa (Seiler et al., 1977). Results for 1 year from Hawaii are shown in figure 7. Carbon monoxide is a gas of considerable importance in tropospheric chemistry. Measurements of its

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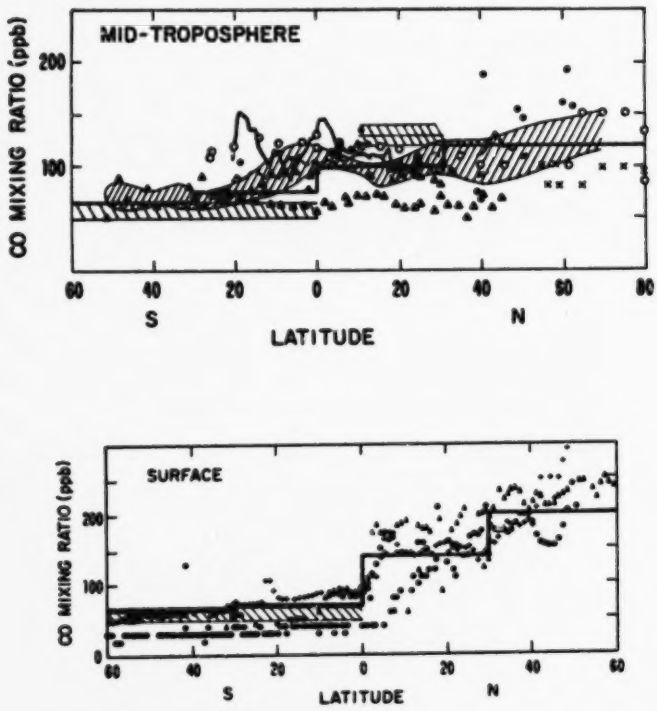
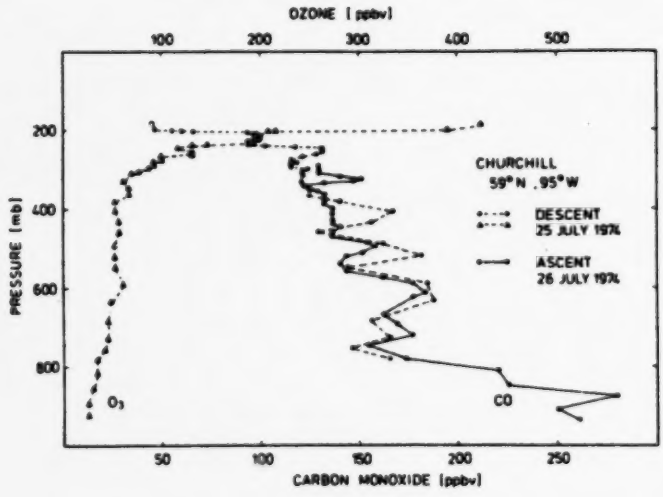


Figure 5.- Latitudinal distributions of CO. (From Logan et al., 1981.)



(a)

Figure 6.- Representative CO profiles. (From Seiler and Fishman, 1981.)

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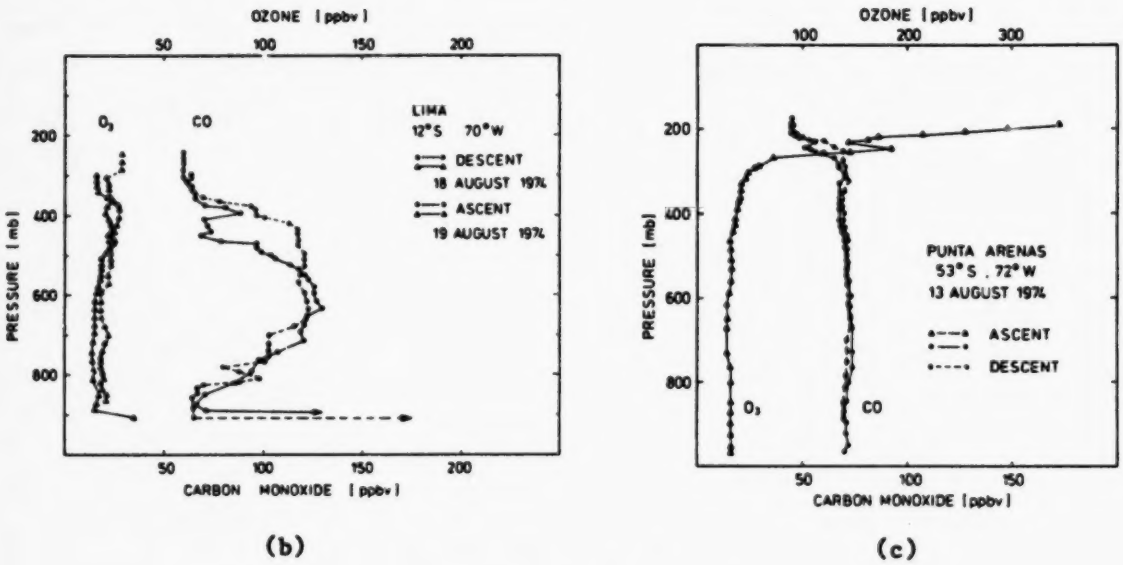

Figure 6.- Concluded.

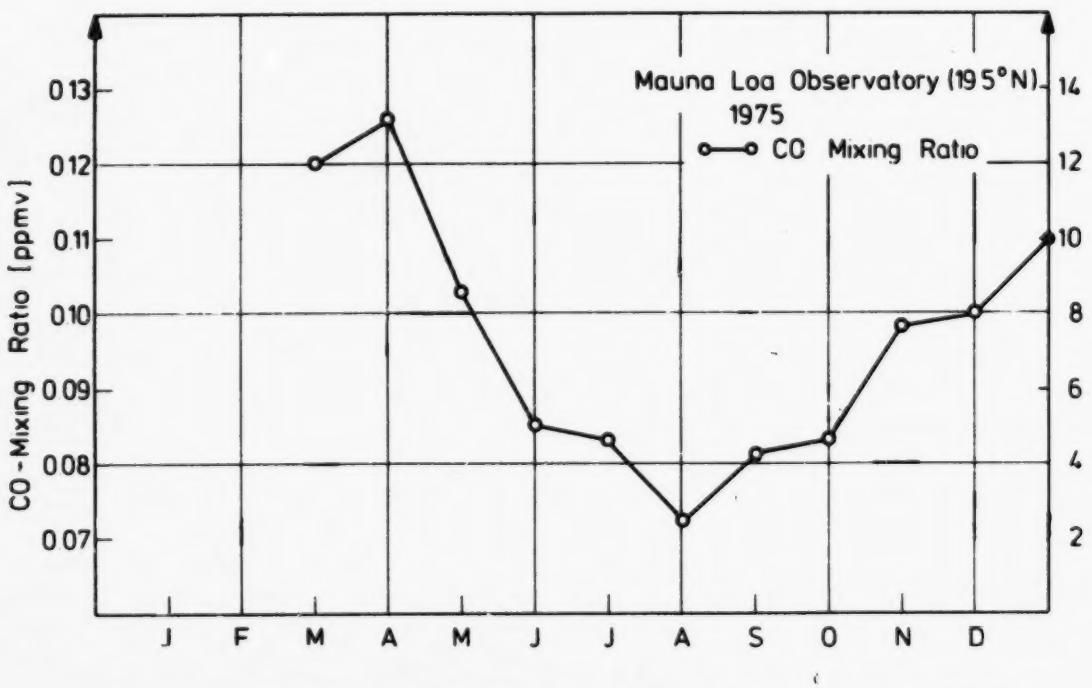

Figure 7.- Seasonal variation of CO. (From Seiler et al., 1977.)

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concentration have been made since 1968, and it is unfortunate that its seasonal behavior is not established and that there are very few measurements from the Pacific.

The lifetime of carbon monoxide is determined by its rate of reaction with OH. Current models suggest that the lifetime of CO is about 1 month in the tropics and at midlatitudes in the summer. Estimates of the sources of CO are given in table 5 (derived from Logan et al. (1981)). The source from combustion of fossil fuels is known to within a factor of about 2. The magnitude of the other sources is much harder to quantify. Plants emit hydrocarbons such as isoprene and terpenes, and it is hypothesized that these compounds are photooxidized in the atmosphere, leading to the production of carbon monoxide. The emission rates of plant hydrocarbons are based on only a few measurements made in the United States, and oxidation mechanisms are not well understood. Consequently, it is difficult to make better than order-of-magnitude estimates of the magnitude of this source of CO. Large quantities of biomass are burned in the tropics in regions where slash and burn agriculture is practiced, and it is difficult to quantify both the extent of burning and the yield of CO. Estimates of the magnitude of the source of CO from oxidations of CH_4 are derived from photochemical models.

TABLE 5. CO BUDGET

(From Logan et al., 1981.)

Sources (10^{12} g yr^{-1})	
Fossil fuel use	~500
Oxidation of natural hydrocarbons	~500 (300 - 1200)
Biomass burning	650 (300 - 1400)
CH_4 oxidation	800 (400 - 1000)
Plants, ocean, etc.	250
Total	2750

Sinks (10^{12} g yr^{-1})	
Reaction with OH	3200 (1600 - 4000)

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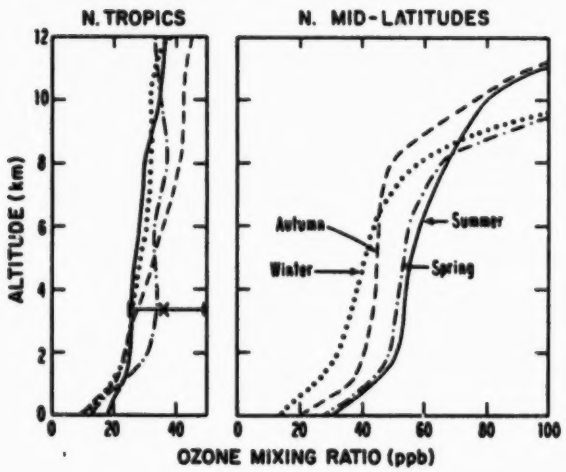
In 1970 it was thought that the automobile was the major source of CO, primarily because there was 3 times as much carbon monoxide in the Northern Hemisphere as in the Southern Hemisphere. The source of the gas was inferred from the measured distribution. Our understanding of the budget for CO has evolved considerably since then, and other sources appear to be important as well. If there were a global perspective of the distribution of CO, more might be learned about other sources (for example, if high values for CO were seen in areas of forest burning). This appears to be an area in which satellite information could play an important role.

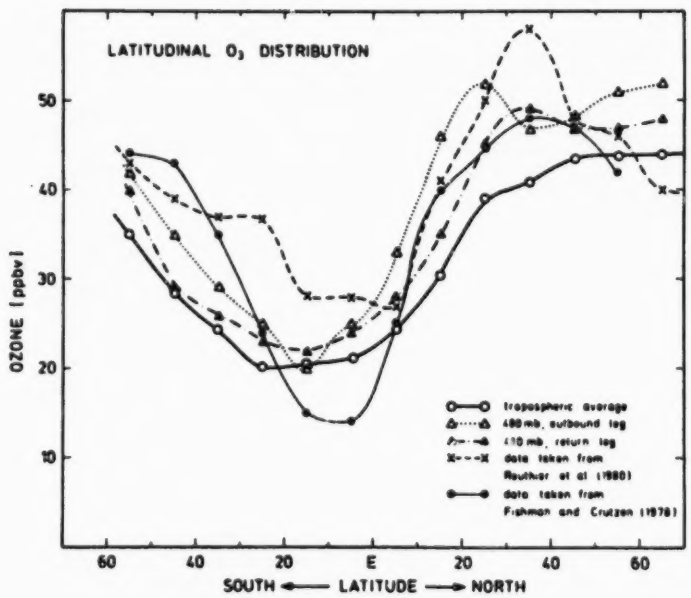
Ozone.- The distribution of tropospheric ozone is not well defined, particularly in the tropics and in the Southern Hemisphere. Most measurements of tropospheric ozone were made as part of a sampling strategy designed to measure stratospheric ozone. The locations of past and present ozonesonde networks are given in table 6. The early measurements of Hering and Borden (1965), referred to in this table, have been analyzed by Chatfield and Harrison (1977). Seasonally averaged vertical profiles of ozone are shown in figure 8(a). The other source of data is a series of aircraft flights that measured the latitudinal distribution of ozone. Some of these measurements are shown in figure 8(b). A major feature of the distribution is that there is less ozone in the tropics than at midlatitudes. It is difficult to infer hemispheric gradients from this type of data, since there is a large seasonal variation in ozone at midlatitudes. The data suggest that there may be more ozone in the Northern Hemisphere than in the Southern Hemisphere. The reason postulated for this asymmetry is that there is more photochemical production of ozone in the northern latitudes than in the southern. Sources of hydrocarbons and NO_x from fossil fuel combustion are located primarily in the Northern Hemisphere, and aircraft (which may produce NO in the upper troposphere) fly mainly in the Northern Hemisphere. The time constant associated with photochemical loss of ozone in the troposphere is about 2 weeks (in the tropics and at midlatitudes in summer). At present the proposed mechanism for this hemispheric asymmetry is rather speculative because of uncertainties in the distribution of NO.

Comments were made previously (see the section entitled Background) about the current understandings of the sources and sinks of ozone. A later section (entitled Transport) discusses further the role of ozone transport in the troposphere and especially stratosphere-troposphere exchange.

Oxides of nitrogen.- Nitric oxide plays an important role in the chemistry of CH and ozone. Photochemical production of ozone is linearly dependent on the concentration of NO. Unfortunately, there are very few data describing the distribution of NO and NO_2 in the troposphere, in part because techniques capable of detecting extremely low concentrations have been developed only recently. Concentrations as low as 4 pptv have been measured in surface air in the tropical Pacific Ocean using the chemiluminescent technique, and values are often below 100 pptv in clean air in the Colorado mountains (measurements made by Kley et al. (1981)). Concentrations are much higher in cities, from tens to hundreds of parts per billion. Optical measurements by Noxon (1978) of the column density of NO_2 in the troposphere are consistent with the low values for NO found in unpolluted air. Nitric oxide and NO_2 are rapidly interconverted (on a time scale of minutes) during the day. The time constant for conversion of NO + NO_2 to nitric acid is about 1 day at midlatitudes in summer. Concentrations of NO and NO_2 (NO_x) are highest over the continents, near source regions, and lowest in marine air. Measurements of NO_x are summarized in figure 9 for continental areas, marine air, and the upper troposphere. The global distribution of NO_x is very poorly defined and there are no measurements from tropical continental regions.



(a) Vertical profiles. (From Logan et al., 1981.)



(b) Latitudinal distribution. (From Seiler and Fishman, 1981.)

Figure 8.- Vertical and latitudinal distributions of O_3.

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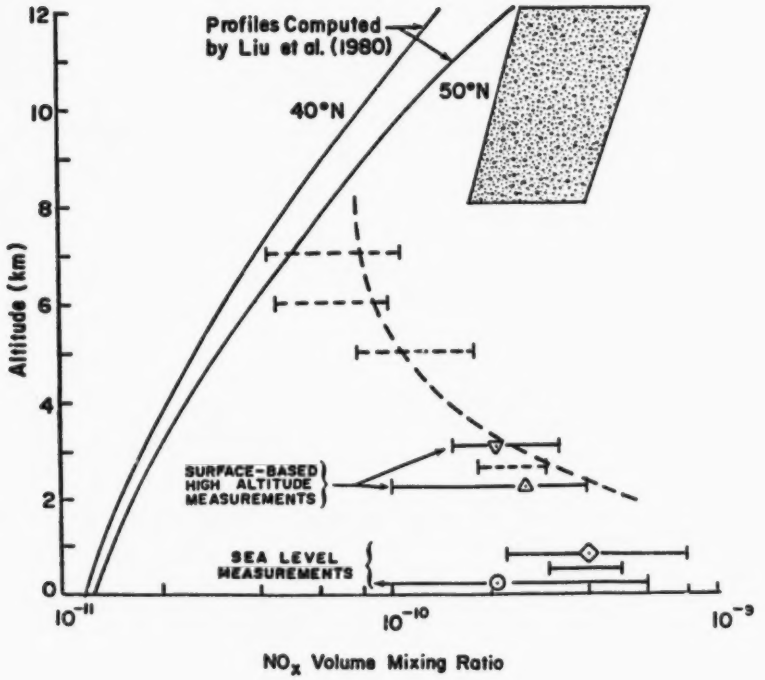
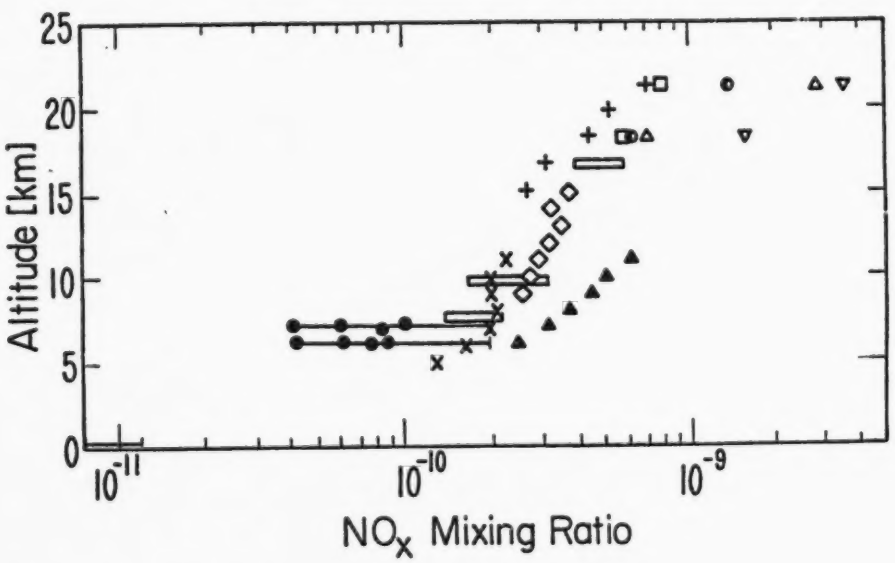


(a) From Fishman (1981).



(b) From Kley et al. (1981).

Figure 9.- NO_x profiles.

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TABLE 6. OZONESONDE NETWORKS

Historical perspective (Hering & Borden, 1965)		
Location	No. stations	Record*
North America (9°N - 77°N)	13	1963 - 1966
	6	1966 - 1969

Present day		
Location	No. stations	10-year record
W. Europe	~6	3
Japan	3	3
Canada	5	2
U.S.	1	1
Australia	1	1

*Different techniques used during each period.

Nitric acid measurements (Huebert and Lazrus, 1980) taken from the GAMETAG project are shown in figure 10. Gaseous HNO_3 was captured on filters. Many of the measurements are below the detection limit, and there appears to be very little gradient with latitude in the upper troposphere from 60°N to 30°S. However, in the boundary layer there is a large maximum at 30° to 50°N, a consequence of anthropogenic sources of NO_x on the North American continent.

Sources of NO_x are summarized in table 7 (derived from Logan et al. (1981) and new data). Combustion of fossil fuels is the major source in North America and western Europe. The amount produced by lightning is based on estimates for the production rate of NO_x in a lightning strike and satellite data for the global lightning flash frequency; there has been speculation that lightning might produce much more NO_x than indicated in table 7. The source of NO_x from biomass burning is highly uncertain, in part because of lack of measurements of NO_x emissions from burning vegetation. The major sources of NO_x in the tropics are not known at present. The lifetime of NO_x is short, and more measurements of the global distribution of NO, NO_2, and HNO_3 would greatly enhance our understanding of the sources of NO_x.

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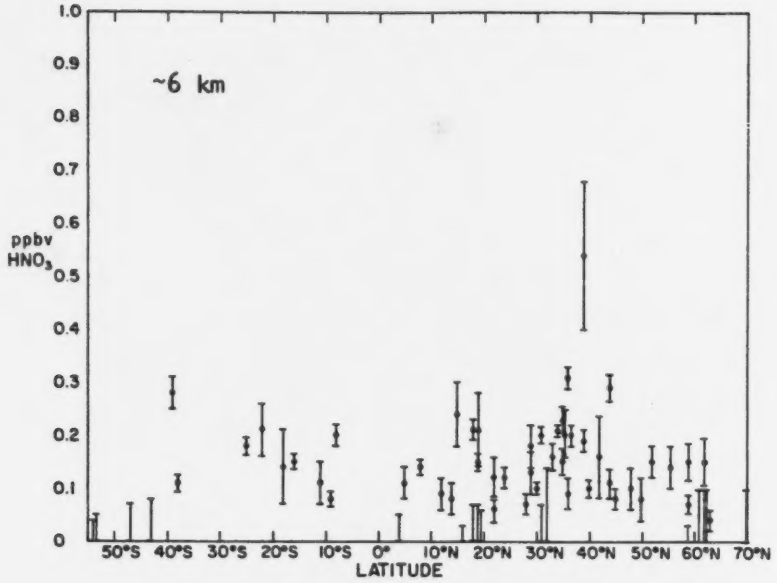
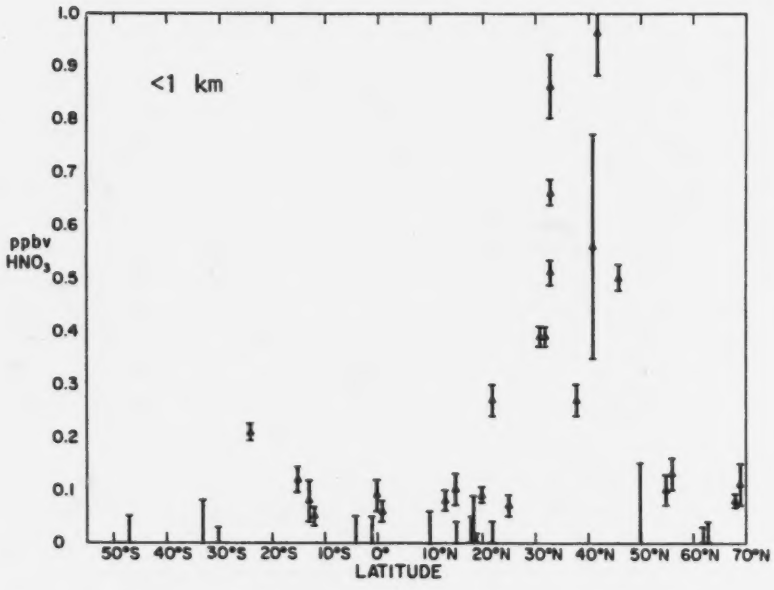


(a) Free tropospheric HNO_3 versus latitude.



(b) Boundary-layer HNO_3 versus latitude.

Figure 10.- HNO_3 measurements. (From Huebert and Lazrus, 1980.)

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TABLE 7. GLOBAL BUDGET FOR NO_x

Sources (10^{12} g N yr^{-1})	
Fossil fuel combustion	20
Lightning	1 - 10
Biomass burning	4 - 50
Microbial activity in soils and the ocean	~10
Oxidation of ammonia	0 - 10
Input from the stratosphere	<1

Sinks (10^{12} g N yr^{-1})	
Precipitation	15 - 50
Dry deposition	10 - 20

Concluding Remarks

The concentrations and lifetimes of the gases which have been discussed are summarized in table 8. These gases are viewed as measurement needs of the Tropospheric Research Program. Ammonia and SO_2 are included in the list because their global distributions are poorly defined at present. These gases were omitted from the earlier discussion because they do not affect tropospheric OH and O_3. Methyl chloroform (CH_3CCl_3), an industrial solvent, appears because it plays a unique role in current analyses of tropospheric chemistry. The budget of methyl chloroform is used to test models of the photochemistry of OH. Its release rate to the atmosphere is known to ~20 percent, its distribution in the atmosphere has been measured since 1972, and the only sink for CH_3CCl_3 is by reaction with OH; consequently the data for CH_3CCl_3 can be used to test models for the global distribution of OH.

Also included in table 8 are examples of areas in which satellite data have provided (or have the capability of providing) some very useful information for studies of tropospheric photochemistry. Measurements of total ozone, cloud cover, and aerosol distributions and properties are required for radiative transfer models. Satellite measurements of lightning frequency have been used for estimates of sources of NO_x. Satellite imagery has the capability of examining patterns and changes in land use, and might provide information on the extent of biomass burning and deforestation rates. Pollution episodes over North America have been tracked by satellites. Future models of heterogeneous removal of gases and aerosols by rainfall will require information on the global distribution of precipitation.

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TABLE 8. MEASUREMENT NEEDS

Species	Mixing ratio	Lifetime
CH_4	$\sim 1.7 \times 10^{-6}$	4 to 8 years
CO	$0.5 - 2.5 \times 10^{-7}$	Months
O_3	$10^{-8} - 10^{-7}$	Weeks
NO, NO_2	$10^{-11} - 10^{-9}$	Approx 1 day
HNO_3	$\sim 10^{-10}$	Approx week(s)
SO_2	$\sim 10^{-10} - 10^{-9}$	Approx week(s)
NH_3	(?) $< 10^{-10} - 10^{-8}$	Approx week(s)
CH_3CCl_3	10^{-10}	Approx 8 years

Other
Total ozone
Cloud cover
Lightning frequency
Tracking of pollution episodes
Land use
Extent of biomass burning Deforestation estimates Crop areas
Precipitation patterns
Aerosols

TRANSPORT

This section concerns the making of representative remote measurements of trace gases and aerosols in the troposphere and, in particular, discusses the dependence of these measurements on structural differences in the atmosphere. The approach by Danielsen (1968) considers these differences not just qualitatively, as implied by the words troposphere and stratosphere, but quantitatively through the use of quasi-conservative meteorological variables and their correlations with trace gases and aerosols. From these quantitative comparisons we can obtain diagnostic information valuable to both atmospheric and photochemical modelers.

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Atmospheric analyses are usually based on the meteorological quantities directly observed, such as pressure, temperature, humidity, and horizontal velocity components. But these are nonconservative quantities, poorly correlated with the trace species. However, certain combinations of the nonconservative quantities yield quasi-conservative scalars. Trace species whose chemical halflives equal or exceed the physical halflives of these scalars can become correlated with them by atmospheric mixing processes.

The Greek prefix "tropo" means to turn. The troposphere is appropriately named because we think of it as a region of active overturning or mixing. However, it would be a mistake to think that the whole troposphere is generally well mixed. Measurements of nitrous oxide or carbon dioxide do not show any significant horizontal or vertical gradients in the troposphere because these long-lived species are stirred by every available mixing process until they reach a quasi-uniform distribution. In this case the chemical halflives are too long to maintain correlations with the quasi-conservative meteorological scalars in the troposphere. Nevertheless, there is a range of chemical halflives which matches a range of structural features in the troposphere, and, as we shall see, their spatial and temporal variabilities are related. These structures are produced by a combination of differential transport and small-scale mixing. To a first approximation, the transport is adiabatic; therefore the scalars, potential temperature and potential vorticity, are conserved.

The potential temperature, θ, is obtained by integrating the second law of thermodynamics. Assuming no heat transfer (adiabatic) in the process and integrating from the actual pressure (p) to a reference pressure of 1000 mb yields

$$\theta = T\left(\frac{1000}{p}\right)^{0.286} \qquad (1)$$

where T is the actual temperature and θ is the temperature the air would have if it were compressed to 1000 mb, approximately sea-level pressure. Converting from T to θ eliminates the effects of compressibility, allowing us to work with an analog to the temperature of a liquid.

When the atmosphere is heated from below, as it is during the day near the Earth's surface, θ increases and the air becomes unstable to vertical displacements. Vertical mixing develops and the result of this mixing is to make θ constant with height. Therefore, a well-mixed boundary layer is identified by $\partial\theta/\partial z \simeq 0$. Figure 11 illustrates such a boundary layer at Lander, Wyoming. This sounding is an excellent example of an extremely deep well-mixed boundary layer. The ordinate is the logarithm of pressure, the abscissa is temperature, but the isotherms which are skewed about 45° to the right emphasize isothermal layers. The slightly curved lines sloping upward to the left are isotherms of θ. Note that θ is constant from the surface to about 20,000 ft. Lander's elevation is close to 5000 ft, so this represents a 15,000-ft boundary layer.

Trace gases or aerosols will be mixed to a uniform value in the layer and will become correlated with θ. Thus a well-mixed boundary layer can be identified by $\partial\theta/\partial z = 0$ and $\partial\chi_i/\partial z = 0$, where χ is the mixing ratio of the trace species i. In general, boundary layers seldom attain or exceed the depth shown here. These deep layers form only over arid soil in cloud-free skies.

If the troposphere really were well mixed, θ would be independent of height from just above the Earth's surface to the tropopause. Then $\nabla\theta$ would be a horizontal

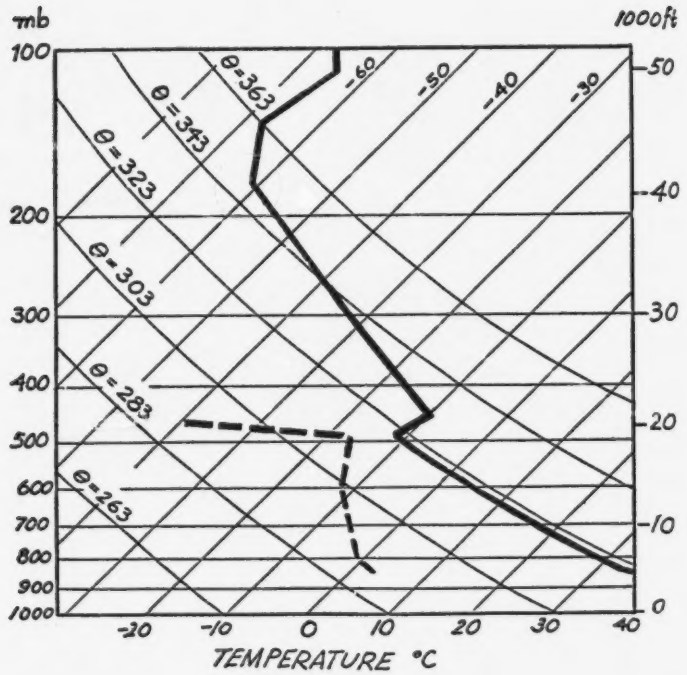

Figure 11.- Temperature (solid line) and dew point temperature (dashed line) at Lander, Wyoming, 0000 UT 13 June 1981. Potential temperatures are labeled in K.

POTENTIAL VORTICITY

$$S = \alpha \nabla\theta \cdot (\nabla \times V + 2\Omega)$$

$$S = \alpha \left[\underset{10^{-7}}{\frac{\partial\theta}{\partial x}} i_1 + \underset{10^{-7}}{\frac{\partial\theta}{\partial y}} j_1 + \underset{10^{-5}}{\frac{\partial\theta}{\partial z}} k_1 \right] \cdot \begin{bmatrix} \underset{10^{-2}}{\left(-\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)} i_1 \\ \underset{10^{-6}}{\left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} + 2\Omega_y\right)} j_1 \\ \underset{10^{-4}}{\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} + 2\Omega_z\right)} k_1 \end{bmatrix}$$

$$S = \alpha \left[\left(-\frac{\partial\theta}{\partial x}\frac{\partial v}{\partial z} + \frac{\partial\theta}{\partial y}\frac{\partial u}{\partial z} \right) + \frac{\partial\theta}{\partial z}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} + 2\Omega_z \right) \right]$$

$$S = \alpha \frac{\partial\theta}{\partial z}\left(\frac{\partial v}{\partial x_\theta} - \frac{\partial u}{\partial y_\theta} + 2\Omega_z \right) = \alpha \frac{\partial\theta}{\partial z}(\zeta_\theta + f)$$

VORTICITY EQUATION

$$\frac{d}{dt} \ln(\zeta_\theta + f) = -\nabla_H \cdot V_\theta$$

STABILITY EQUATION

$$\frac{d}{dt} \ln\left(\alpha \frac{\partial\theta}{\partial z}\right) = +\nabla_H \cdot V_\theta$$

Figure 12.- Definition of potential vorticity and reduced form based on neglect of very small terms. Lower two equations apply under adiabatic approximation.

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vector and the troposphere would be unstable to horizontal displacements. Such displacements are produced by the large-scale internal waves which would amplify and lead to quasi-horizontal mixing. A vertically well mixed troposphere is therefore improbable, and as observations indicate, only the diurnally produced surface boundary layers achieve such a state.

The second quasi-conservative scalar is derived from the equations of mass, momentum, and energy conservation. It is called the potential vorticity and is denoted here by S such that

$$S = \alpha \nabla\theta \cdot (\nabla \times V + 2\Omega) \qquad (2)$$

where α is the specific volume, $\nabla\theta$ is the three-dimensional gradient of θ, and the term in parentheses is the absolute vorticity, the sum of the vorticity relative to the Earth, $\nabla \times V$, and the vorticity of the Earth, twice the angular velocity Ω. For a small air parcel,

$$\frac{dS}{dt} = \alpha(\nabla \times V + 2\Omega) \cdot \nabla \frac{d\theta}{dt} \qquad (3)$$

Large values of S are generated in the upper stratosphere as a result of increasing heating with height by ultraviolet absorption by ozone; i.e., $\nabla(d\theta/dt)$ has a positive vertical component. At the Earth's surface during the day, this vector is reversed and S decreases toward zero. Between about 30 km and the ground, S is quasi-conserved. Thus, to a first approximation, S is similar to ozone; it is created in the upper stratosphere, transported downward into the troposphere, and destroyed at the Earth's surface.

When equation (2) is expanded, as shown in figure 12, it includes several products of small terms which can be neglected. To an excellent approximation, the potential vorticity can be reduced to the simple product

$$S = \alpha \frac{\partial\theta}{\partial z} (\zeta_\theta + f) \qquad (4)$$

where $\partial\theta/\partial z$ is a measure of the stability of an air parcel displaced vertically (the static stability), $\zeta_\theta + f$ is a measure of the stability of an air parcel displaced horizontally (the inertial stability), ζ_θ is the vertical component of the vorticity on a θ surface, and f is the vertical component of 2Ω.

The equations at the bottom of figure 12 indicate the importance of S; i.e., it is independent of the horizontal convergence at constant θ. When the large-scale waves propagate relative to the air, horizontal divergence simultaneously changes the vorticity and stability, leaving S unchanged.

The potential vorticity derived by Ertel (1942) is one of the most important diagnostic variables for the Earth's atmosphere. Consider first the longitudinal-seasonal mean distribution, and then a synoptic distribution. Figure 13 shows the θ isotherms (continuous lines) and the isotachs of west wind speed (dashed lines) from which the mean distribution of S can be computed. Also shown is the mean tropopause (heavy dashed line) which slopes upward from 7 km at the pole to about 17 km at the equator. Note that the θ isotherms slope upward to the north in the troposphere and downward to the north in the stratosphere. This reversal in slope is related through the thermal wind equation to a reversal in the vertical shear of the west wind from positive in the troposphere to negative in the stratosphere; thus the mean tropopause intersects the mean jet.

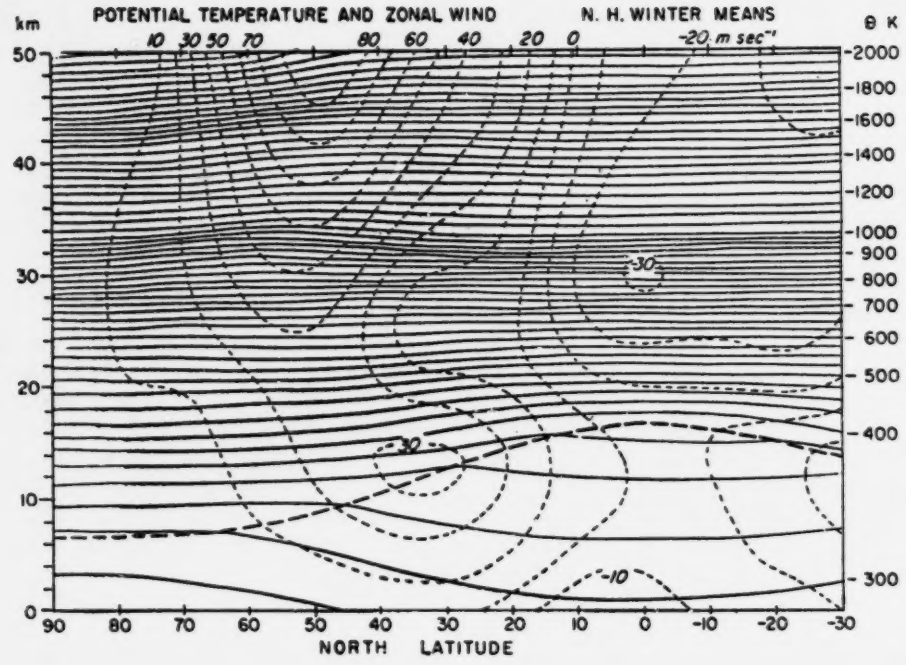

Figure 13.- Northern Hemispheric zonal winter mean of potential temperature $\bar{\theta}$ (continuous lines) and west wind velocity U (dashed lines).

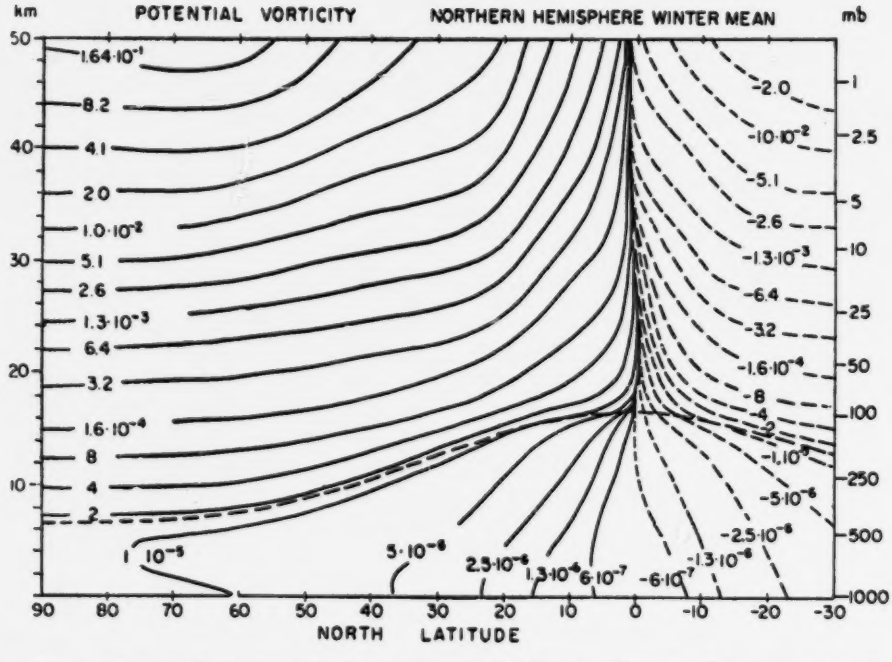

Figure 14.- Potential vorticity computed from figure 3, expressed in units of cm^2 deg g^{-1} s^{-1}. Negative values in Southern Hemisphere are contoured by dashed lines.

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As shown in figure 14, the mean tropopause coincides with a constant value of $\bar{S}$ from the pole to about 15°N. This result is very significant because air of extratropical stratospheric origin can be determined solely by $S > \bar{S}_T$, where $S > \bar{S}_T$ is the tropopause threshold value. If air with $S > \bar{S}_T$ is encountered in the troposphere (and, in fact, it often is), then it should be characterized by large concentrations of ozone and other trace species of stratospheric origin. Similarly, if small values of S are found in the stratosphere, its origin was either the troposphere or the low-latitude stratosphere. In either case, anomalous concentrations of trace species would be expected.

One example of the synoptic distribution of S and its relationship to ozone will now be examined. Included in figure 15 are both S (light continuous) and $\bar{S}$ (heavy continuous) contours, along with the mean tropopause (dashed line). Values of $S > 800$ (units of 10^{-7}cm^2 deg g^{-1} s^{-1}) are shaded to facilitate visual recognition of spatial variability. Note that at high latitudes and elevations $S \simeq \bar{S}$, but large deviations are characteristic of the lower stratosphere and upper troposphere. In particular, a very large positive anomaly is located at about 11 km at station 72490 (Bedford, Mass., the left of the two vertical lines), where $S \simeq 8\,\bar{S}$. The expectation is that this air will have come from higher elevation and will contain large concentrations of ozone.

Evidence of the ozone anomaly is presented in figure 16, which is an ozonagram from Bedford taken on the same day and time as the cross section. The ozone partial pressure went off the scale near 12 km. Suspecting an instrument malfunction, the operators released another ozonesonde, which established the profile as valid. Note also a minimum of ozone above the maximum and the corresponding minimum in S at Bedford in the cross section. But partial pressure is another nonconservative scalar; to make a direct comparison with S we must convert p_{O_3} to χ_{O_3}. Two such comparisons are shown in figure 17. The left profiles correspond to those made are Bedford, the right to those from Tallahassee, Fla. (station 72214) in figure 16.

Here there is a rather close correlation between S and χ_{O_3} in the stratosphere; remarkably so, because $S = C\chi_{O_3}$ with the same constant being applicable at both stations. The relationship becomes weaker in the troposphere, suggesting an ozone loss at Bedford in the middle and lower troposphere and an ozone gain at Tallahassee. Alternatively, the potential vorticity could have been changed by a gradient of diabatic heating. With just this limited data base we cannot choose between the two alternatives.

Recalling that $\bar{S}_T \simeq 160$ in these units, note that the tropopause at Bedford is approximately 2 km below the local mean and that extruded layers or tongues of stratospheric air slope downward both to the north and south of Bedford. Reference to figure 18 indicates that these extrusions are beneath the polar jet, which is westerly to the south of Bedford and easterly to the north of Bedford, consistent with flow around an intense low centered close to Bedford. This same extruded layer was penetrated by aircraft 2 days earlier over Colorado as part of Project Springfield (Danielsen, 1964, 1968). Although ozone was not measured aboard the aircraft (no reliable fast-responding sensor was available), radioactivity of stratospheric origin was, and as the aircraft penetrated this layer extremely high concentrations were encountered, consistent with the large value of S.

Another example of a stratospheric extrusion into the troposphere which was traversed by an aircraft now equipped to measure ozone is shown in figure 19. Note the strong horizontal gradient of θ and wind speed beneath the jet core. As the aircraft traversed these gradients the ozone increased rapidly while the humidity

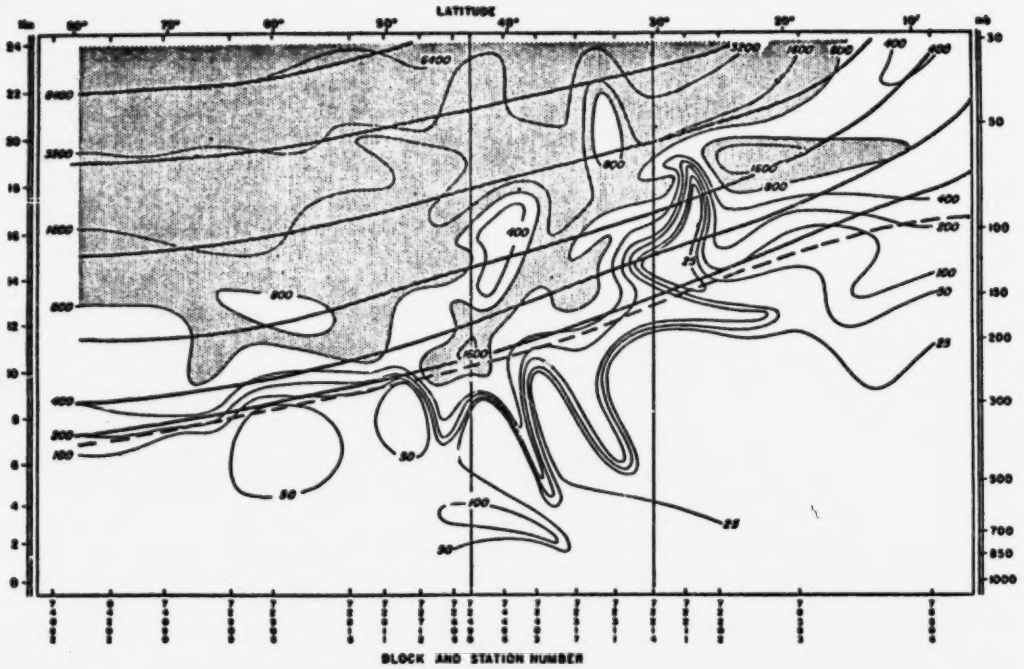

Figure 15.- Synoptic distribution of potential vorticity S (light lines) superimposed on zonal spring mean distribution $\bar{S}$ (heavy lines). Mean position of tropopause is indicated by dashed line. Units of S and $\bar{S}$ are 10^{-7} cm^2 deg g^{-1} s^{-1}.

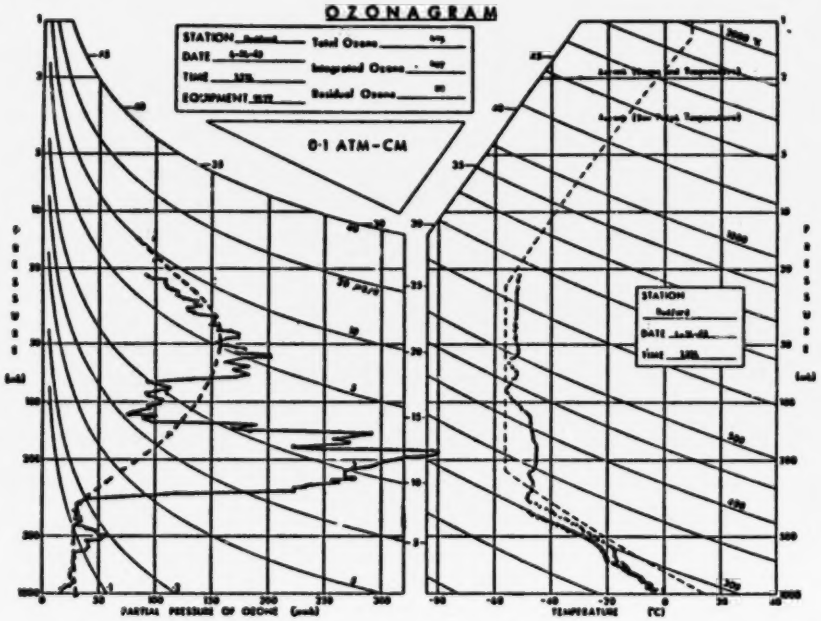

Figure 16.- Ozonagram from Bedford, Mass., April 24, 1963. Dashed line in left diagram is spring mean for Bedford. (After Hering and Borden, 1965.) Thin lines sloping down to right in left diagram are ozone mass mixing ratio isolines. Temperatures and dew point temperatures are given in right diagram.

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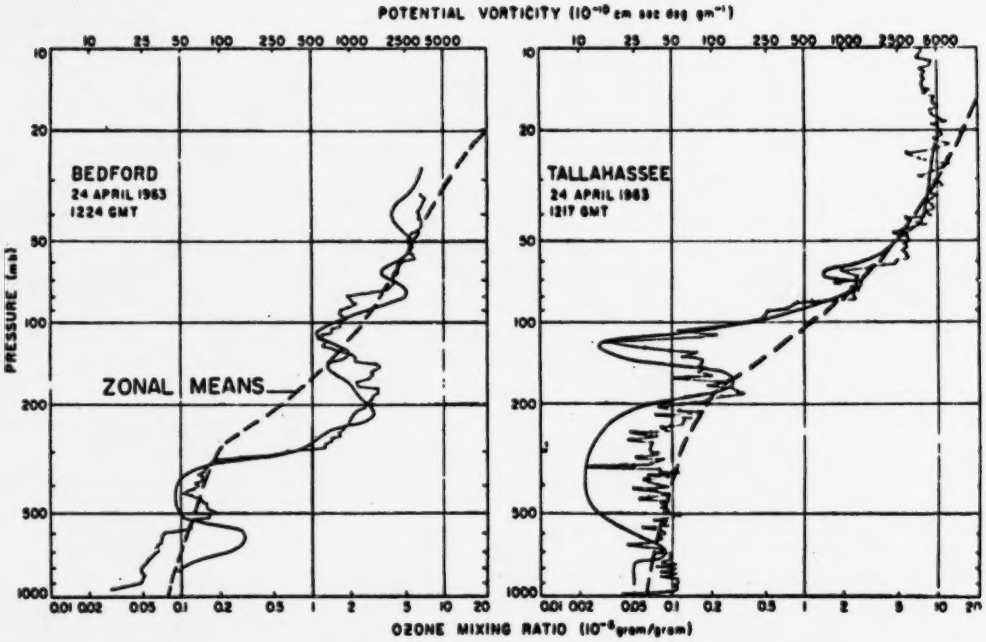

Figure 17.- Ozone mixing ratio χ_{O_3} profiles (detailed thin lines) from Bedford, Mass. and Tallahassee, Fla., April 24, 1963, superimposed on potential vorticity S profiles (thin lines). Dashed lines are zonal spring means of S for the appropriate latitudes.

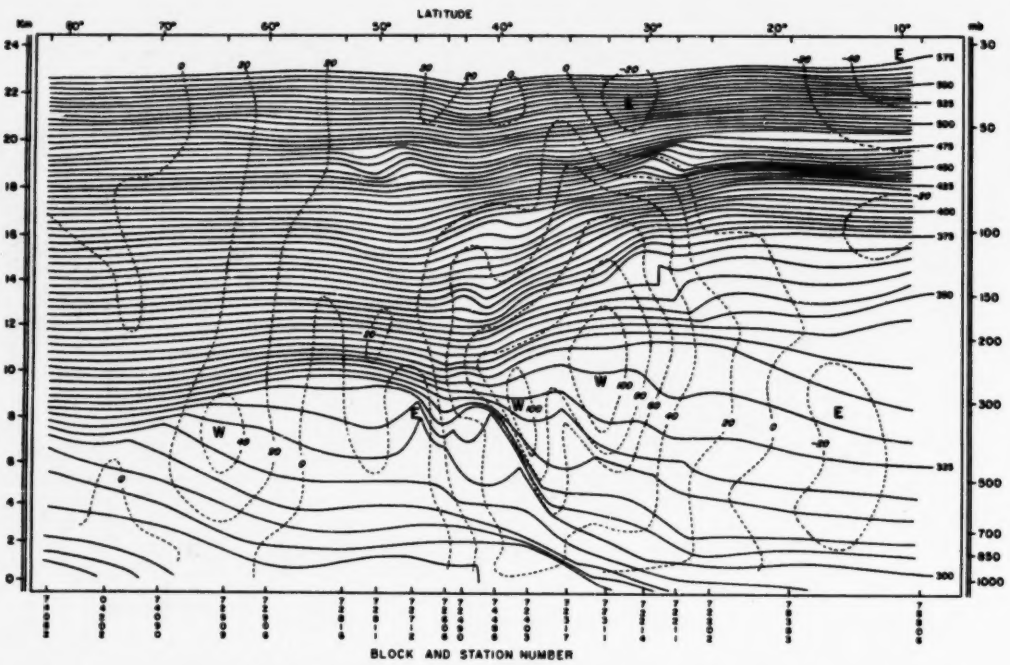

Figure 18.- Cross section of potential temperature, θ, and west wind velocity, U, from which S of figure 5 was computed. Local maximums in west and east winds are given by W and E, respectively. (After Danielsen, 1968.)

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decreased. The profiles versus time in figure 20 clearly indicate the presence of stratopheric air in the troposphere. In this case the stratospheric air, although diluted by mixing with adjacent tropospheric air, extends all the way to the Earth's surface. (For more details see Danielsen and Mohnen (1977).)

The ozonesonde measurements were made every Wednesday, beginning in April 1963, at a fixed network of stations over North America. They represent the traditional mode of atmospheric sampling, semicontinuous in the vertical and discrete in the horizontal. Direct evidence of stratospheric extrusions into the troposphere by this method of sampling was sparse. The measurements were too infrequent and too far apart.

The major objective of Project Springfield, which was organized and directed during April 1963 (see Danielsen, 1964), was to verify the phenomenon of tropopause folding by first predicting where and when it would occur and then dispatching aircraft to make semicontinuous measurements horizontally across the shortest dimension of the predicted stratospheric layer. During April this was accomplished in each of five attempts, flown mostly on weekends over the western and central United States. By the middle of the week these same layers were advecting off the eastern coast.

The extruded layers are extremely asymmetrical, with the narrowest dimensions about 100 to 150 km perpendicular to the wind and the longest dimensions 1000 to 2000 km along the axis of the main jet. A rather dense network of soundings is required to detect the layers, and it is essential to compute the potential vorticity to distinguish them from frontal zones which form in tropospheric air. Case studies and numerical modeling experiments show that stratospheric air flows adiabatically from the lower cyclonic stratosphere into the troposphere as each major wave cyclone develops and amplifies in the extratropical troposphere. This transport is also verified by isentropic trajectory analyses.

A point to stress here is that the large-scale wave cyclones tend to concentrate gradients of potential temperature and potential vorticity in the troposphere, thereby increasing the potential for dynamic instability and subsequent small-scale mixing. They also produce the organized patterns of vertical motions which transport air from the boundary layer into upper "free" troposphere and vice versa. Examples of these transports are given in figures 21 and 22.

Figure 21 illustrates the streamlines on a surface of constant θ_{ve}, a generalization of θ which is quasi-conserved for moist, isentropic processes. Moist air ascending from the surface over New England condenses as it turns clockwise (anticyclonically) over eastern Canada. In this ascent it quickly becomes upper tropospheric air. To the west and south of the storm center over Lake Michigan the descending flow carries upper tropospheric and lower stratospheric air down to the surface boundary layer. The predominance of anticyclonically curved flow is illustrated schematically in figure 22.

Considering the complexities of the large-scale three-dimensional flows, it is understandable that no simple prescription can be made for tropospheric sampling. In general, in situ sampling requires both vertical and horizontal paths. Remote measurements have the advantage of determining the important horizontal gradients on the regional or global scale. When combined with a few in situ measurements for calibration and comprehensive diagnostic analyses of the atmospheric structure, including potential temperature and potential vorticity, representative sampling can probably be attained most effectively and economically.

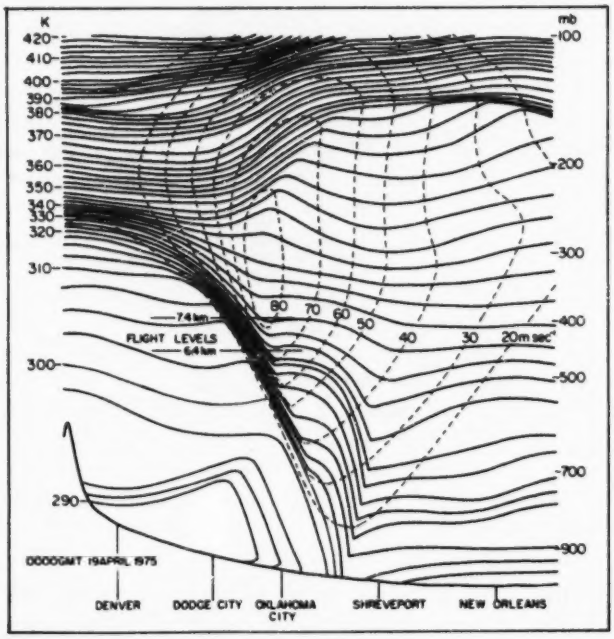

Figure 19.- Cross section of potential temperature and southwest wind velocity, April 18, 1973. Indicated flight levels denote traverses of folded tropopause made by NCAR's Electra aircraft. (After Danielsen and Mohnen, 1977.)

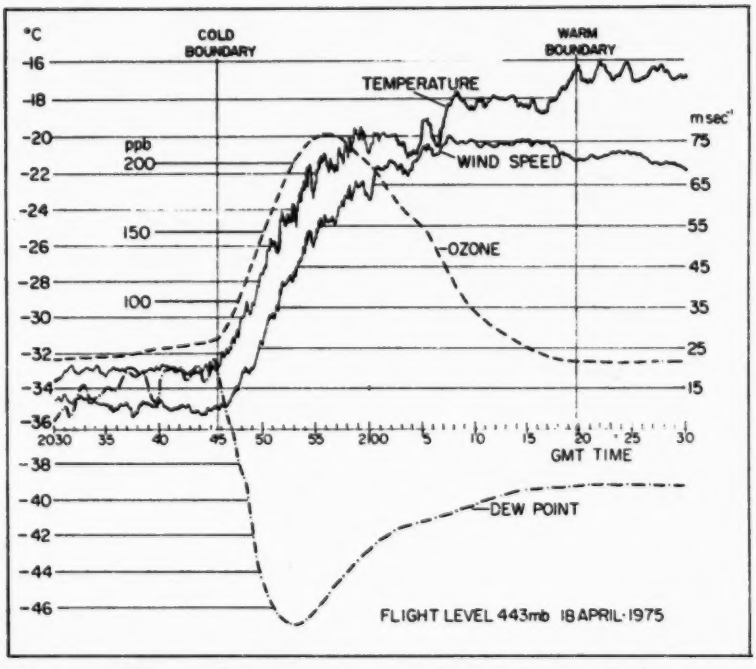

Figure 20.- Flight profiles of temperature, dew point, wind speed, and ozone mixing ratio measured during first traverse of folded tropopause from cold to warm side. (After Danielsen and Mohnen, 1977.)

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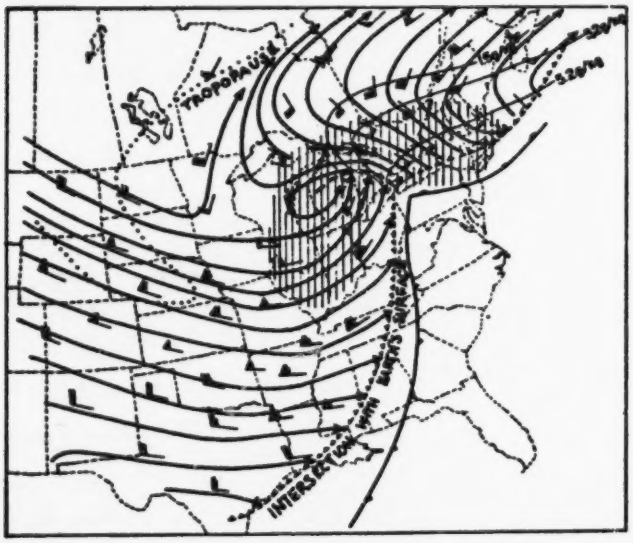

Figure 21.- Winds and streamlines on a moist isentropic surface (constant θ_{ve} = 300 K) for 1200 UT, March 26, 1964. Note steep slope of surface from ground to tropopause. Decrease in water vapor with ascending flow over New England is evident from χ_v saturation isolines.

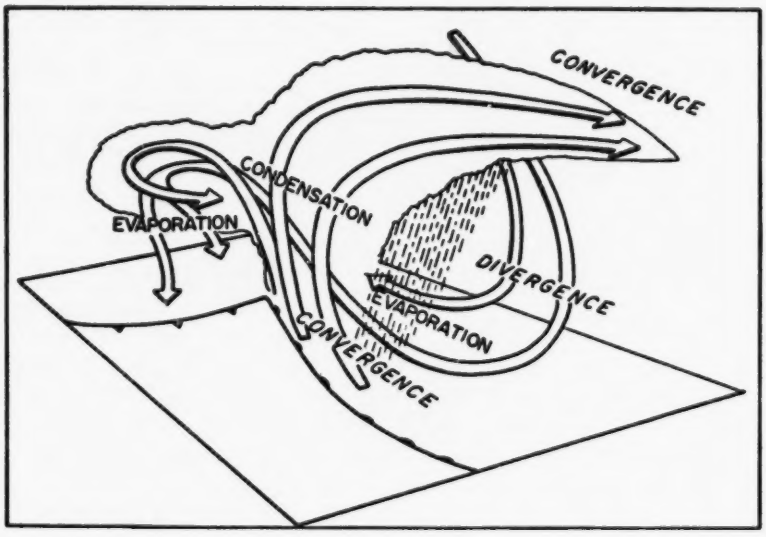

Figure 22.- Schematic diagram of three-dimensional flows with amplifying wave cyclone. These flows rapidly remove and replace boundary-layer air.

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In closing it is well to emphasize again the importance of analyzing for quasi-conservative atmospheric scalars and taking advantage of the correlations established by mixing processes between these scalars and the mixing ratios of trace species.

SUMMARY OF NEEDS

Species listed in table 9 are potential measurands for passive remote sensors with a capability for horizontal resolution as fine as 20 km, vertical resolution of at least two layers in the troposphere, and total burden accuracies in the range of 5 to 20 percent. Understanding the chemistry involved in the formation of aerosols and in depletion processes such as acid rain imposes similar requirements on passive remote sensors for the measurement of aerosol optical thickness and aerosol size distribution.

TABLE 9. KEY TROPOSPHERIC TRACE SPECIES

Species	Mixing ratio	Lifetime
H_2O	$10^{-3} - 10^{-2}$	-
CH_4	$\sim 1.7 \times 10^{-6}$	4 to 8 years
CO	$0.5 - 2.5 \times 10^{-7}$	Months
O_3	$10^{-8} - 10^{-7}$	Weeks
NO, NO_2	$10^{-11} - 10^{-9}$	Approx 1 day
HNO_3	$\sim 10^{-10}$	Approx week(s)
SO_2	$\sim 10^{-10} - 10^{-9}$	Approx week(s)
NH_3	(?) $< 10^{-10} - 10^{-8}$	Approx week(s)
CH_3CCl_3	10^{-10}	Approx 8 years

The long-term role for passive sensors with regard to transport parameters is the measurement of selected tracer species and standard meteorological variables in three dimensions with temporal repeats every 3 to 9 hours. Such measurements would be made in the vicinities of large-scale meteorological events on a worldwide basis.

Some additional passive sensing measurements, perhaps acquired from separate observing platforms, that aid in the understanding of sources, transport, and sinks of key tropospheric species are (1) weather conditions such as cloud cover, precipitation patterns, and lightning, (2) pollution episodes as indicated by satellite imagery of "hazy blobs," and (3) land use parameters such as the extent of biomass burning, deforestation estimates, and crop coverage areas. Measurement accuracy requirements for these quantities cannot be precisely defined (in some cases even qualitative measurements are useful) but the spatial and temporal resolution scales should be consistent with those specified for the other measurands.

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ROLE OF PASSIVE REMOTE SENSORS

(SENSOR SYSTEMS PANEL REPORT)

BACKGROUND

The role of passive remote sensors is determined by how well the various sensing techniques can be used to make the measurements that are needed for tropospheric research and operational use. The focus is on the trace gaseous species and the aerosols. For such species, the absorption and scattering features appropriate for remote sensing occur primarily in the spectral region from 0.3 to 20 μm. Microwave systems are not as promising as infrared systems for sensing of trace species and aerosols because of the excessive broadening of the spectral features at pressures occurring in the troposphere. Microwave sensors, however, can play a role in measuring meteorological variables such as rain rate. The sensing system techniques considered by the Sensor Systems Panel included all of those covered in the generic sensor reviews (see Appendix C) presented to the entire workshop, as well as specific sensors that are currently flying on satellites or are in the near-flight stage.

At the outset of the Sensor Systems Panel discussions it was clear that many specific questions relative to determining the feasibility of a given system for tropospheric soundings (e.g., spectral bandwidth coverage and resolution, optimum SNR, specific versus nonspecific system, etc.) could not be answered within the time frame of the workshop. Moreover, it was apparent that to obtain definitive answers to the many questions that were left unanswered by this panel would require several extensive studies that were beyond the scope of the workshop objectives. But the panel discussions that took place and the recommendations that resulted did begin to answer the complex and relatively new problems of remote sensing of the troposphere. Furthermore, based on NASA's successful experience in stratospheric sensing and satellite meteorology, the outlook is bright for quantitative measurement of trace gaseous species and aerosols in the troposphere.

To a great extent, many of the panel recommendations are based upon the actual and projected performance of current satellite systems (e.g., TIROS N, Nimbus 7, and DMSP) as well as results from analyses of several passive techniques which are in the planning or near-flight state (e.g., MAPS, HALOE, ATMOS, and LHS). It was felt that consideration of those existing systems would provide a reasonable basis from which new technology requirements could be extropolated, as well as a gauge by which the effectiveness of new technology might be judged.

CURRENT OPERATIONAL PASSIVE REMOTE SENSORS

Because of the panel's heavy reliance upon past performance of passive systems which are currently on free-flying satellites, the following discussion is included to outline their salient features. This review is intended only to highlight the basic measurements systems, with emphasis on measurement capabilities and the measurement accuracy required to yield a given result.

Since the inception of NASA's space program, passive sensing systems have been key components of virtually all free-flyer payloads. Passive techniques have enjoyed this early and dominant role primarily due to their simplicity, low weight, and low power consumption. The early systems were, for the most part, visible and IR imagers devoted to measurement of cloud cover and the thermal and reflected solar radiation from the Earth's atmosphere. Application of the early atmospheric sensing

systems was primarily associated with tracking frontal systems for weather forecasting purposes. A profusion of more sophisticated remote sensing systems quickly followed (e.g., SIRS, IRIS, ITPR, HIRS, VTPR, etc.), and these have resulted in operational satellites (TIROS, Nimbus, and DMSP) providing temperature, humidity, ozone data, and other parameters on a global basis. The early systems typically consisted of rather broadband filters backed by cryogenically or radiatively cooled detectors to measure IR thermal radiation emitted from the Earth's atmosphere or visible and UV solar radiation reflected from the Earth's surface or atmosphere. Each succeeding generation of passive sounders has resulted in a progressive refinement of the observations needed to deduce useful atmospheric parameters. These refinements have typically included wider spectral coverage, higher spectral resolution, and narrower fields of view, along with improved detection technology. Improvements in each area lead, in general, to more accurate measurements with improved vertical and horizontal spatial resolution for these nadir-viewing tropospheric sensors. It should be noted that, at the same time, similar sensing technology was also being used for experimental sensing of the stratosphere in a limb-viewing mode, and, serendipitously, some high-vertical-resolution measurements were made in the upper troposphere.

A major thrust of many of the current operational satellites has been the global monitoring of temperature, water vapor, and ozone profiles. A key issue associated with passive nadir-viewing sensors is their ability to provide vertically resolved measurements of these atmospheric parameters, and this clearly is of importance for tropospheric sensing. The vertical resolution achieved from spectrally resolved radiance data is intimately tied to the temperature and pressure dependence of the spectral band or line within the instrument passband, and therein lies the ultimate limitation of passive systems to obtain high vertical discrimination. Temperature or gas-density profiles can in principle be inferred from a set of radiance data through inversion of the radiative transfer equation. For example, inversion of the radiative transfer equation, given the vertical profile of the absorbing gas (e.g., CO_2), leads to a vertical temperature profile consistent with the radiation detected within several spectral bands. (CO_2 is often used for temperature sounding because it has a constant mixing ratio up to approximately 90 km in altitude.) Conversely, the vertical profile of a given gas can in principle be extracted from the radiative transfer equation, given a temperature profile and the radiances measured within an absorption band of the gas of interest. The vertical resolution of passive techniques is typically characterized by a weighting function (the derivative of the spectral transmissivity with respect to pressure, or a similar function which is related to the normalized radiance signal versus altitude) associated with each sensing channel. The shape and vertical width of the weighting functions are dependent upon the spectral characteristics of the absorbing gas and the spectral resolution of the various sensing channels. In general, narrow spectral channels tend to lead to narrow weighting functions (i.e., high vertical resolution); the minimum half-width for the extreme condition of monochromatic resolution is on the order of 4 to 5 km in the troposphere. The channels that are heavily attenuated by the atmosphere (e.g., band or line center channels) generally give rise to weighting functions which peak at higher altitudes (e.g., greater sensitivity to higher altitudes), while the more transparent channels are able to penetrate deeper into the atmosphere and yield weighting functions that peak at lower altitudes.

The more recent sounding satellites (e.g., DMSP 5D-1/F4, launched 6/6/79; Nimbus 7, launched 10/24/78; and TIROS N, launched 10/13/78) combine a wide range of instruments designed for measurement from the UV bands to millimeter wavelength regions of the spectrum. While the various spectral regions often complement each other for many applications, the excessive broadening at tropospheric pressures experienced by absorption features in the millimeter spectral region restricts application of the

millimeter sounders to the stratospheric region if any vertical discrimination is desired. For this reason the remaining discussion will not include any of the millimeter wavelength instruments on these satellites.

Some relevant facts regarding tropospheric sensors on these three satellites and on Nimbus 4 are summarized in table 10. On board the DMSP satellite is the Special Sensor H (SSH). This IR filter radiometer has 15 channels designed to obtain the total burden of ozone along with vertical temperature and water vapor profiles. On board the TIROS N is the High Resolution Infrared Radiation Sounder (HIRS 2). This IR filter-type radiometer has 16 channels designed to measure vertical temperature profiles, water vapor mixing ratio, and total ozone content. On board the Nimbus 7 is the Temperature/Humidity Infrared Radiometer (THIR) and the Solar Backscatter

TABLE 10. REMOTE SENSING EXPERIENCE

Satellite and remote sensor	Quantity inferred radiance channels		
	Temperature	Water vapor	Ozone
DMSP			
SSH	Vertical profile, -6 ch., 13.4-15 μm (CO_2)	Vertical profile, -8 ch., 18.7-28.3 μm	Total burden, -1 ch., 9.8 μm
TIROS N			
HIRS-2	Vertical profile, -7 ch., 13.4-15 μm (CO_2) -5 ch., 4.24-4.57 μm (N_2O,CO^2)	Vertical profile, -3 ch., 6.7-8.3 μm	Total burden, -1 ch., 9.7 μm
Nimbus 7			
THIR	Surface, -1 ch., 10.5-12.5 μm	Total burden, -1 ch., 6.5-7.0 μm	-
SBUV	-	-	Vertical profile, -12 ch., 0.25-0.34 μm
TOMS	-	-	Total burden, -6 ch., 0.31-0.38 μm
Nimbus 4			
SIRS B	Vertical profile, -7 ch., 13.4-15 μm (CO_2)	Vertical profile, -6 ch., 436-280 cm^{-1}	- -
IRIS	Vertical profile, thermal emission spectra from 400 cm^{-1} to 1600 cm^{-1} with spectral resolution of 2.8 cm^{-1}	Vertical profile	Vertical profile

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Ultraviolet/Total Ozone Mapping System (SBUV/TOMS). The THIR is a two-channel IR filter-type radiometer which was designed to measure the water vapor content of the atmosphere and the underlying surface temperatures. The SBUV/TOMS on Nimbus 7 consists of two tandem UV Ebert-Fastie monochrometers and a single UV monochrometer. This system is designed to measure the vertical profile and total burden of ozone. The Satellite Infrared Spectrometer (SIRS B), flown on the Nimbus 4 satellite, is included because it contained six water vapor channels and seven temperature channels in the same spectral regions used by the SSH, and because it represents a different instrument technology. This instrument was an F/5 Ebert-Fastie grating spectrometer providing 14 simultaneous spectral channels. Finally, the IRIS, also flown on Nimbus 4, is included. It is an interferometer which yields (after Fourier transformation) high-resolution spectral data over the same spectral region.

The inversion of measured radiances to temperature values and gas concentrations requires that the radiance measurements be made with good signal-to-noise ratios (SNR). Signal-to-noise ratios are important in that they affect how accurately the inversions can be made and indicate the sensitivities that are currently achieved. The noise equivalent spectral radiances (NESN) for the SSH temperature channel vary from 0.11 to 0.30 erg/sec cm^{-2} sr cm^{-1} for the SSH temperature channels and from 0.09 to 0.33 erg/sec cm^{-2} sr cm^{-1} for the SSH water vapor channels (Klein et al., 1976). Ozone total burden radiances are measured with NESN of 0.05 erg/sec cm^{-2} sr cm^{-1} by the SSH instrument and with a SNR of 1×10^5 by the TOMS instrument, while ozone profile radiances are measured by the SBUV instrument with a SNR of 5×10^3. The NESN of the IRIS instrument is between 0.5 and 1 erg/sec cm^{-2} sr cm^{-1}.

The other important measurement parameter when inverting from spectral radiances to vertical profiles is the vertical weighting function. Table 10 shows that for inferring temperature, the number of CO_2 channels and their wavelength intervals are practically the same for the SSH, HIRS 2, and SIRS B instruments. Figure 23 shows the corresponding weighting functions for the SSH instruments, which are typical for all of the instruments. Similarly, figure 24 illustrates weighting functions for the SIRS B instrument for sensing water vapor profiles.

Results from the HIRS and SSH, along with those from the predecessor of these radiometers, the SIRS B, have demonstrated the capability of remotely measuring atmospheric temperature profiles. CO_2 spectral radiances made with NESN values on the order of 0.2 erg/sec cm^{-2} sr cm^{-1} can be inverted to yield temperature profiles with accuracies of 2° to $4^{\circ}C$ and a vertical resolution of 3 to 5 km. Nevertheless, improved accuracy and vertical resolution are desired, particularly in the troposphere, both for many meteorological applications and for the use of these profiles in the remote sensing of troposphere trace gaseous species. The incremental improvement needed for tropospheric research uses varies with the particular sensor system and species being considered and cannot be stated quantitatively at this time. The accuracy and vertical resolution capabilities of current temperature sounders, however, are presently not the limiting factors in the performance of tropospheric sensors.

Extraction of gas density profiles from radiance measurements obtained from a nadir-viewing system places a greater demand on instrument sensitivity, accuracy of supporting data, and retrieval algorithms. In general this is asscociated with the fact that at a given frequency the upwelling radiance is a function of the temperature and constituent profiles in the atmosphere. Retrieval of temperature profiles is performed assuming a known constituent profile (e.g., CO_2), whereas for retrieval of an unknown gas profile the radiance data are dependent upon both temperature and absorbing gas profiles and require a simultaneous measurement of the temperature

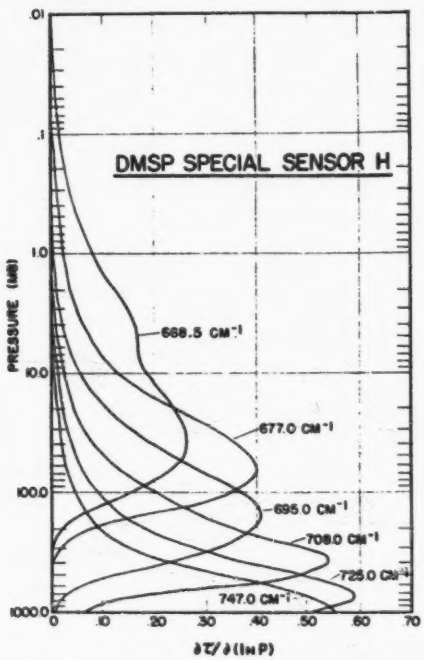

Figure 23.- Typical SSH weighting functions. (From Klein et al., 1976.)

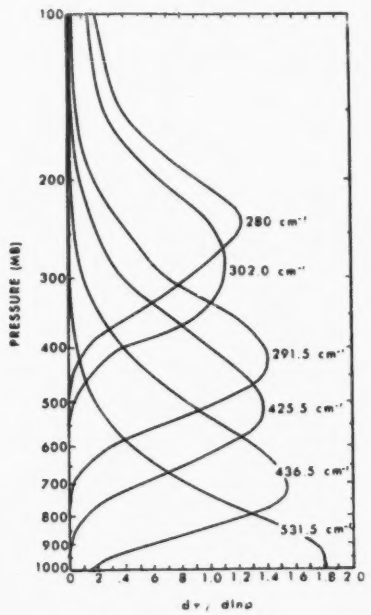

Figure 24.- Typical SIRS weighting functions for water vapor profiles determinations. (From Smith, 1970.)

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profile. Because of this dependence, a set of frequencies cannot be chosen to ensure uniform sampling through the atmosphere; i.e., weighting functions depend upon the concentration. Moreover, for low-level soundings the surface contributions to the upwelling radiance become more important. For many tropospheric species of interest the overall retrieval problem of inferring gas profiles is further complicated by their low concentration, weak absorptions, or interfering effects from other species, any one of which results in a small signal change for large changes in concentration (i.e., low signal contrast).

Water vapor and ozone, however, are the two atmospheric species for which nadir-viewing soundings systems have been applied with some degree of success. Results obtained for total water vapor concentration have shown good agreement with independent radiosondes. Results for water vapor profiling are also very encouraging. In figure 24 it should be noted that while the H_2O weighting functions appear to be evenly distributed with respect to altitude, this is dependent upon the assumed H_2O profile (Smith, 1970). With the SIRS B channels, retrieved profiles are shown to agree favorably with radiosonde data (e.g., figure 25). Results obtained to date from the two operational satellites also are very encouraging. For example, results from a recent analytical study of the SSH H_2O-sensitive channels indicate that under some conditions water vapor profiles can be obtained from a selected subset of these channels. In general, however, retrieval of humidity profiles suffers from a high degree of channel redundancy (i.e., overlap of weighting functions). Smith suggests that a different set of spectral channels leading to three or four independent weighting functions would provide more accurate and reliable profiles. Extensive analysis of the H_2O data channels from the HIRS 2 on TIROS N has just begun. The initial results are also encouraging; it appears that for operational applications, reliable moisture data can be obtained for at least two layers of the troposphere.

The SBUV system can provide profiles for stratospheric ozone from approximately 10 mb to 1 mb. The TOMS system yields total burden measurements of ozone; however, with only approximately 10 percent of the total ozone burden residing in the troposphere, the TOMS data are not expected to be particularly sensitive to changes in the tropospheric ozone level.

To conclude this section on sensors that have obtained results aboard satellites, two figures are included to illustrate the capability of the Nimbus 4 IRIS instrument. The radiance spectra obtained from the CO_2, H_2O, and O_3 bands are shown in figure 26 and the corresponding inversion results are shown in figure 27 for vertical profiles of temperature, relative humidity, and ozone concentration, respectively.

ADVANCED SENSOR CONCEPTS

With the performance levels and system requirements of passive instruments that have successfully performed on satellites as a background, the Sensor Systems Panel considered each of the generic sensors with respect to the potential for providing total burden and/or vertical profiles with at least a two-level resolution within the troposphere (e.g., the mixing layer (1 to 5 km) and the free troposphere (5 to 10 km)). For the sake of organization, these concepts can be classified as either species-specific or spectral survey type instruments. The species-specific types sense radiance in a limited spectral interval that is associated with absorption or scattering features of specific gaseous species or aerosols. The spectral survey types sense radiances from broad spectral bands that may contain contributions from many species. The species-specific group includes optical filter radiometers, gas

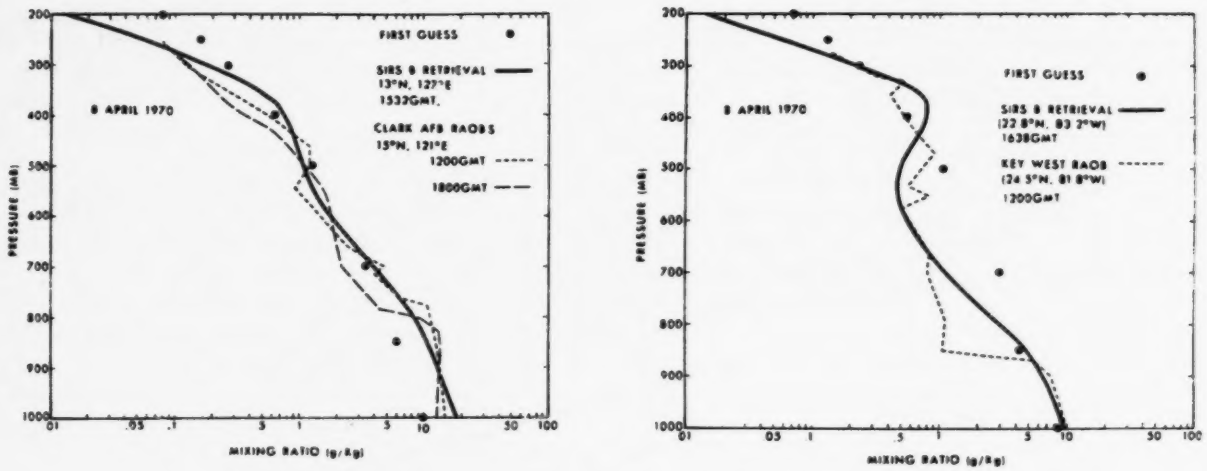

Figure 25.- Two comparisons between SIRS B calculated and radiosonde observed water vapor profiles. (From Smith, 1970. Reprinted by permission of Macmillan Journals, Ltd.)

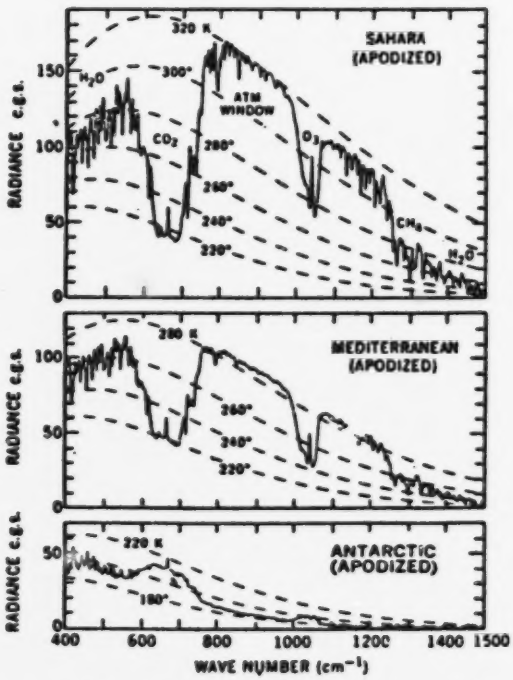

Figure 26.- IRIS D (Nimbus 4) thermal emission spectra. The apodized spectra have a spectral resolution between 2.8 cm^{-1} and 3 cm^{-1}. Radiances of blackbodies at several temperatures are superimposed. (From Hanel and Conrath, 1970.)

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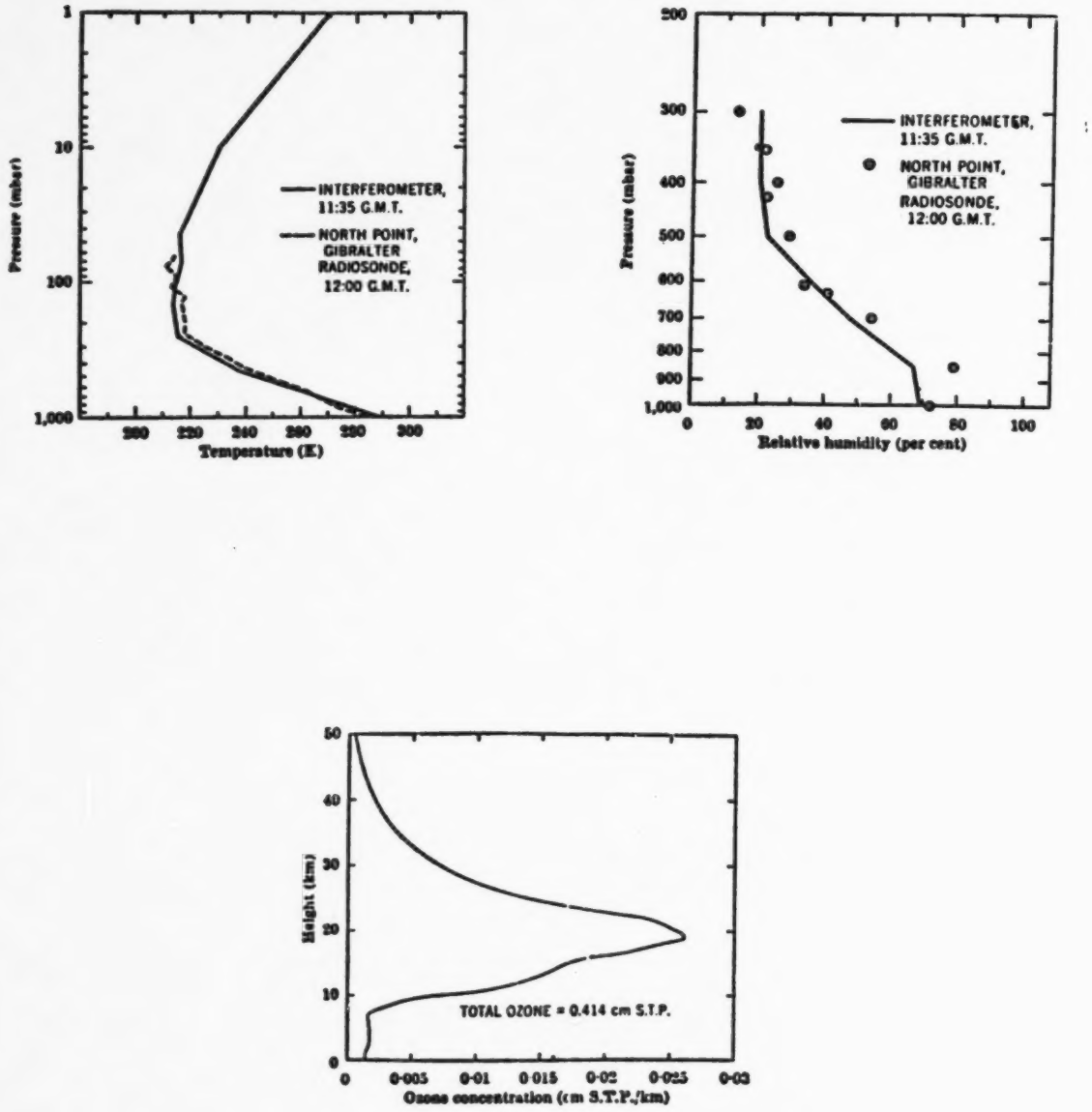

Figure 27.- Temperature, humidity, and ozone profiles derived from the Mediterranean spectra of figure 26. (From Hanel and Conrath, 1970.)

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filter radiometers, correlation grating spectrometers, and laser heterodyne techniques. The spectral survey group includes scanning interferometers and diffraction grating spectrometers. The grating instruments actually span both broad generic groups, but are here considered as survey types.

Species-Specific Sensors

Optical filter radiometers.- This type of sensor has been successfully used to sense tropospheric temperature and water vapor profiles, as illustrated by the discussion of the SSH and HIRS instruments in the previous section. In addition, several concepts developed for the stratosphere using limb sensing and for Earth resources applications using nadir sensing show promise for tropospheric applications. For example, the LIMS instrument on Nimbus 7 measured several stratospheric gases, and the SAM II instrument, also on Nimbus 7, made global measurements of stratospheric aerosols. Some of the limb observations sucessfully penetrated deep into the troposphere. Advanced limb-sensing instruments may be able to sense specific gaseous species and some aerosol characteristics. The limb-sensing option for the upper troposphere is discussed later in this panel report.

Radiometry for lower tropospheric aerosols.- The quantitative monitoring of tropospheric aerosols is important in several areas, e.g., tracking of pollution episodes and dust outflows, global modeling of the relationships of aerosols to molecular species, climatology, climate-directed radiative transfer calculations, and assessment of aerosol effects on other remote sensing experiments (e.g., the inversion of spectral data). Existing satellite sensors (Landsat, GOES, NOAA 6) have already been used to determine the optical thickness of aerosols over oceans (Griggs, 1981a, b). Quantitative measurements of aerosols over land have not been demonstrated due to the problems of the high and variable land albedo, although qualitative monitoring of high-pollution episodes has been achieved. In the near term, the existing AVHRR sensor (two channels) on NOAA 6 can be used to routinely produce global maps of aerosol optical thickness over oceans, although additional work is needed to develop efficient algorithms to routinely invert the available satellite data. Current measurements provide only total burden data with little prospect for obtaining the vertical distribution with passive nadir-viewing instruments. Measurements have recently been made in two spectral bandpasses, thus giving some information on the aerosol size distribution.

Future needs include the following:

1. Radiative transfer and satellite operations data to develop methods for removing the effects of high and variable surface reflectivity in determining aerosol optical thicknesses over land

2. Ground truth experiments to assess the extent to which variable surface reflectivity effects may be removed in obtaining spectral optical thicknesses over land via proposed sensing strategies

3. Measurements made at more wavelengths with narrower bandwidths in order to obtain sufficient spectral thickness information to invert for aerosol size distributions (algorithms are available); for example, new sensor systems with six to eight channels of ~0.01 μm bandpass extending from approximately 0.4 to 1.0 μm and including certain near-IR windows (~1.6 and 2.2 μm) to provide additional information about larger particle sizes

4. Radiative transfer studies to assess the prospect of using polarization measurements to retrieve aerosol refractive index (i.e., related to composition)

Gas filter radiometers.- Gas filter radiometry can be exemplified by the MAPS and PMR instruments (Reichle, 1976; Hesketh et al., 1977). The MAPS instrument, which flew on the second Shuttle mission, is a two-channel system designed to measure CO. The PMR is currently used as part of NOAA's TIROS N temperature sounding system and provides three channels sensitive to thermal emissions from stratospheric CO_2. Both of these instrument techniques offer the potential of providing total and/or profile data on a number of tropospheric species. Of the species of gases identified in the section on measurement needs, gas filter radiometer techniques are capable of measuring CO, CH_4, and O_3 with a spatial resolution of 20 km. With an improvement in sensitivity there is also the possibility of measuring NO and HNO_3. In addition to its importance in tropospheric chemistry, the measurement of these gases has direct application to atmospheric transport modeling; e.g., one- or two-layer CO measurements for global transport, CH_4 measurements for gradient flow, and the combination of tropospheric and stratospheric O_3 measurements for stratospheric-tropospheric interchange.

On the first Shuttle test flight of the MAPS instrument, the weighted vertical average of CO will be measured using the two channels characterized by the weighting functions shown in figure 28. The measurement accuracy for the weighted vertical average of CO is about 20 percent. Analysis has shown that by the proper selection of pressure of the absorbing gas in the cell, the altitude at which the signal function peaks (i.e., weighting function) can be shifted between 7 and 12 km with a width of ± 3 km at the 50-percent point. Moreover, unpublished analysis of the MAPS instrument shows that by improving the instrument sensitivity by a factor of 30, the altitude at which the instrument signal function peaks can be extended down to 1.5 km and up to 15 km. Of interest also are results from an analysis of a PMR, which illustrated that signal response functions (fig. 29) with peaks near ground level can also be obtained by proper design of the pressure modulator drive (Orr and Rarig, 1981). For completeness it should be noted that the HALOE instrument selected for flight on the UARS spacecraft and the SAMS pressure-modulated radiometer flown on Nimbus 7 are designed for making limb-viewing measurements of the stratosphere with good vertical profiling. There is, however, no limb-sensing experience in the troposphere with the gas filter radiometric technique.

The major disadvantage of current gas filter radiometry technology is associated with the limited range of gases which can be contained in a gas cell. The current MAPS instrument has the capability of obtaining similar measurements of CH_4 simply by replacing CO with CH_4 in the absorbing gas cell. With increased sensitivity, NO measurements are also a possibility. For short-duration missions, such as typical Shuttle flights, one can envision extension of this technology to other gases such as ozone and nitric acid. This is particularly true since a change in gas cell pressure as large as 100 percent can be tolerated over the mission lifetime. However, for longer missions improvements in gas cells and gas generation will be required. This will be discussed further in the report of the Sensing Technology Panel.

Fabry-Perot spectrometers.- The Fabry-Perot spectrometer is a generic type of narrow-band spectrometer which is normally designed to be species-specific because of its limited spectral scanning range. No such instrument has yet been designed for tropospheric sensing; however, high-resolution solid etalon technology has been developed for stratospheric limb trace-gas measurements. A solid etalon instrument, the Cryogenic Limb Array Etalon Spectrometer (CLAES), will be tested on a Shuttle

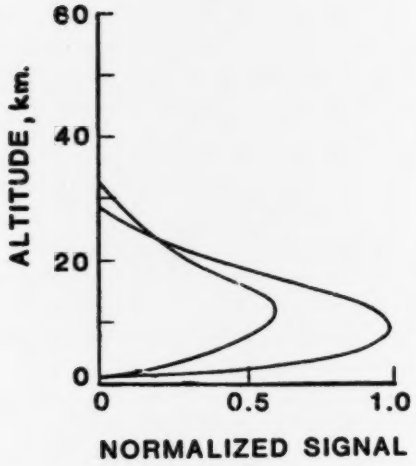

Figure 28.- MAPS weighting functions for two carbon monoxide (CO) gas pressure cells.

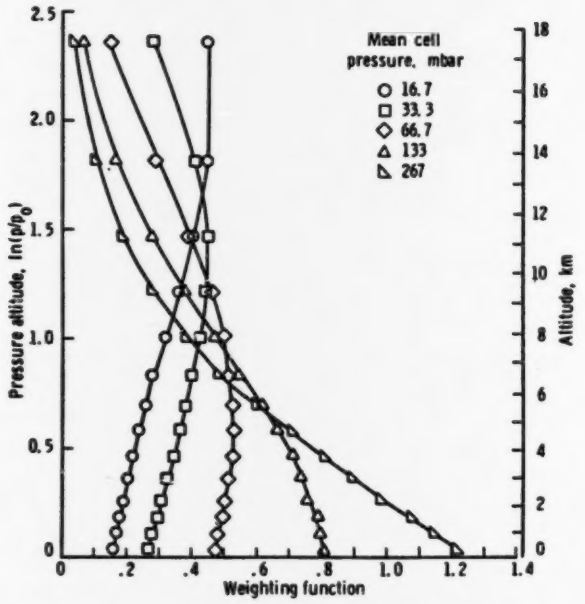

Figure 29.- Pressure modulated radiometer (PMR) weighting functions for CO for a 1-cm cell at five mean cell pressures. Integral of each curve over altitude is normalized to 1. (From Orr and Rarig, 1981.)

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mission and is planned for a 2-year-lifetime UARS mission. CLAES uses solid etalons operated at 55 K along with small detector arrays to measure stratospheric profiles (from 10 to 60 km) of O_3, NO_2, N_2O, HNO_3, CH_4, and several other trace species.

Correlation grating spectrometers.- Correlation grating spectrometers using mechanical correlation masks in the spectrometer exit plane have been developed as specific gas sensors and have found their largest application in the UV-visible part of the spectrum (Ward and Zwick, 1975). The correlation spectrometer could be employed in the infrared spectral regions, although this has not been pursued to date. In the UV-visible spectral region molecular absorption bands tend to be broad, and increasing resolution beyond that of the band structure is neither necessary nor useful. The correlation masks designed to date have used up to four sets of seven spectral slits per set. The integrated spectral radiance, passing through the correlation masks onto a single detector (photomultiplier), is processed in real time within the sensor to yield the integrated line-of-sight amounts of gas.

Ground-based upward-looking measurements have been made of stack-gas emissions for mass emission rate estimation, plume tracking, plume dispersion parameter estimation, etc. The correlation spectrometer as a downward-looking sensor has its greatest value (1) in sensing subtle spectral changes (a few parts in 10^4) where direct examination of the complete radiance spectrum would not readily show the changes caused by the presence of trace gas absorption, and (2) in fast sampling of preselected spectral regions where source intensities are changing or where insufficient time is available for a complete spectral data gathering. Such measurements would provide total burden information with high horizonal resolution but little vertical discrimination.

The large dynamic range A/D (analog-to-digital) converters and high data rate handling capability now in existence have reduced the need for mechanical masks. An advanced correlation spectrometer with linear detector arrays (for imaging purposes) at preselected spectral locations or with area arrays (spectral and spatial dimensions) located in the spectrometer focal plane would enable electronic correlation as well as spectroradiometric measurements, giving experimenters the option of electronically adjusting the correlation function in postflight analysis.

The use of the UV-visible part of the spectrum for tropospheric trace-gas detection is limited, since (1) the initial radiance source is reflected sunlight, and therefore complete diurnal studies cannot be done, and (2) only a limited number of gases (SO_2, NO_2, and O_3) have useful electronic absorption structure in this part of the spectrum. For global tropospheric chemistry and transport studies, NO_2 and SO_2 are the two most promising gases amenable to this technique. In the case of O_3 there is a need for highly accurate spectral data for investigating ground albedo effects and advancing data retrieval algorithms.

Laser heterodyne techniques.- Two trends that have been evident in passive remote sensing are (1) improvements in horizontal spatial resolution, and (2) increased spectral resolution. Although these two goals are desirable, an improvement in spatial resolution (i.e., smaller instantaneous fields of view (IFOV) and/or integration distances) and an increase in spectral resolution (i.e., a decrease in the instrument spectral band) both result in a decrease in the signal level available to the instrument. Infrared heterodyne radiometers and spectrometers, however, provide an inherently narrow IFOV (e.g., ~0.2 mr) and a narrow spectral resolution (e.g., typically <0.06 cm^{-1}) with near-quantum limited sensitivity. Furthermore, tunable infrared heterodyne techniques can provide a set of weighting functions which, in principle, result in several layers of discrimination below 10 km. Shown

in figures 30 and 31 are the weighting functions that have been obtained for a hypothetical receiver for measurement of H_2O and CH_4, and the resulting H_2O and CH_4 profiles obtained assuming a SNR of 20 (Seals, 1973). Similar results were obtained when considering the heterodyne technique for temperature soundings. While such results are clearly enticing and appear to offer a technique suitable for tropospheric sounding, they are offset by the fact that to achieve a modest SNR of 20 requires integration times on the order of 60 to 80 seconds (signal-to-noise ratios are greater at longer wavelengths). Because of the long integration times necessary to achieve sufficient SNR's, a geosynchronous satellite appears to be the most suitable space platform for this type of instrument in the nadir-viewing mode.

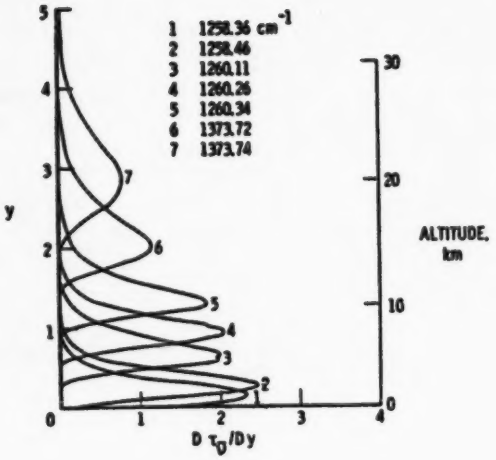
Actual instrument experience has been with non-nadir-viewing modes. The Langley Research Center's IHR instrument (Hoell et al., 1980; Hoell, 1981) has been used in an upward Sun-looking mode from the ground and on the Convair 990 aircraft for NH_3 measurements, and the LHS instrument (Allario et al., 1980) is being designed for measuring specific species with absorption features in the 8- to 12-μm region on future Shuttle flights in a solar occultation mode. Upper tropospheric measurements over clear regions are a possibility for instruments like the LHS in the limb-viewing mode.

Spectral Survey Sensors

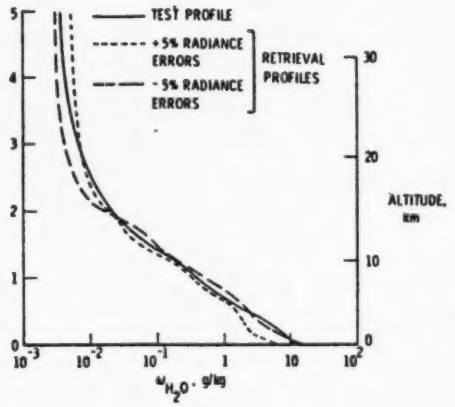
Grating spectrometers.- As noted earlier, the grating spectrometer is an instrument which can be operated in either a survey mode (i.e., scanning) or a species-specific mode (e.g., fixed grating). Moreover, with the use of multiple slits this system can enjoy a multiplexing capability with simultaneous coverage of several spectral regions. The major disadvantage is the low throughput, particularly for high-spectral-resolution application.

A great deal of experience has been obtained using grating instruments from various platforms (Murcray, 1978). As noted earlier, the SBUV/TOMS is a grating system used for operational measurements of ozone. Also, the SIRS B, flown on Nimbus 4, was an IR multichannel grating system. Results from the SIRS B demonstrate the feasibility of this type of system for simultaneous measurements of temperature and water vapor profiles. SAGE, a grating instrument flown on the AEM satellite, has also been successful in making stratospheric and upper tropospheric measurements of aerosols and ozone using the limb-viewing geometry (McCormick et al., 1979).

Interferometers.- The scanning interferometer offers all the characteristics that seem to be desirable for measurement of tropospheric gaseous species, namely, high sensitivity, the potential for high spectral (and species) specificity, and large information content (i.e., information on all absorbing gases in a broad spectral region). However, these advantages are accompanied by more complexity, poor horizontal resolution (due to the requirement for long path-difference scanning), and large amounts of data. Notwithstanding, over the past 10 to 15 years various interferometer systems have been used from ground, aircraft, balloon, and satellite platforms, and recent improvements in computer technology have greatly alleviated the problems associated with the large data flow from interferometers. Of particular interest here is the performance of the IRIS instrument flown on Nimbus 3 and 4 (and on some planetary missions) (Hanel and Conrath, 1970). This instrument recorded thermal emission spectra of the Earth between 400 and 1600 cm^{-1} with an apodized spectral resolution of 2.8 cm^{-1}. The noise-equivalent radiance (i.e., SNR = 1) was between approximately 0.5 and 1.0 erg/sec cm^2 sr cm^{-1}. Scan time for each interferogram was approximately 13.1 seconds. Samples of the thermal emission spectra

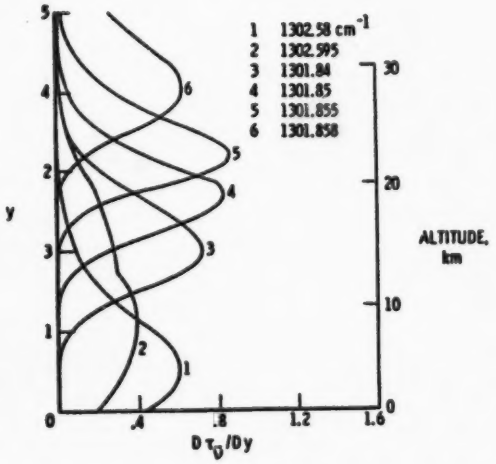


(a) Weighting functions.

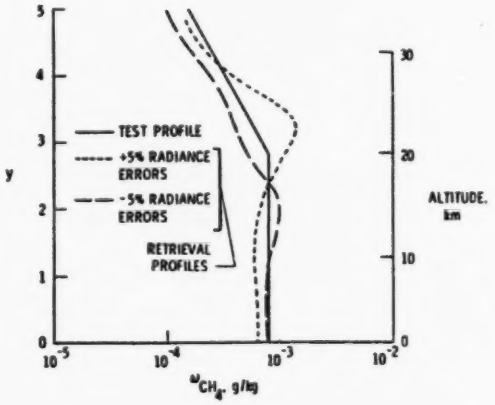


(b) Profile retrieval.

Figure 30.- Heterodyne radiometer weighting functions and profile retrieval for water vapor. (From Seals, 1973.)



(a) Weighting functions.



(b) Profile retrieval.

Figure 31.- Heterodyne radiometer weighting functions and profile retrieval for methane. (From Seals, 1973.)

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recorded on Nimbus 4 are shown in figure 26. Temperature, relative humidty (water vapor), and ozone profiles that were inferred from these spectra are given in figure 27. The large information content available from the scanning interferometer is evident from the emission spectral scans shown in figure 26. Note in particular that along with H_2O, O_3, and CO_2, absorption features of CH_4 have also been identified. This type of data provides the simultaneous measurement of temperature necessary for gas profile retrievals.

NASA is supporting the development of another interferometer, ATMOS (Atmospheric Trace Molecules Observed by Spectroscopy), to be flown on future Shuttle missions. This instrument and its development status are described by Morse (1980). This Fourier transform spectrometer is designed for the spectral range from 2 to 16 μm, where six bands cover this range with all spectral elements within a band observed simultaneously at a limiting spectral resolution of 0.01 cm^{-1}. Although the initial applications are planned for upper atmospheric measurements using the technique of high-resolution infrared absorption via solar occultation, the instrument advances afford promise for applications in tropospheric measurements. (See, e.g., Farmer et al. (1976) for a report of results from a developmental predecessor to ATMOS.)

DEFINITION OF THE ROLE OF PASSIVE REMOTE SENSORS

Roles of Various Sensors

The preceding sections of the Sensor Systems Panel report have discussed the tropospheric measurement capabilities of current operational systems and the characteristics of a number of near-operational or advanced concepts. However, before discussing possible measurement systems it should be noted that two of the advanced concepts have been eliminated from further detailed consideration because their roles in meeting the measurement and mission needs appear to be limited. These advanced systems, the correlation grating spectrometer and the heterodyne techniques, were eliminated for a variety of reasons.

The current design of the correlation grating spectrometer relies upon UV solar scattering and consequently is restricted to daylight measurements of only SO_2, O_3, and NO_2. A particularly restrictive aspect of this technique is that it provides only total burden measurements with no capability of obtaining profiles of the detected species. Finally, the basic concept of correlation spectrometry can be implemented postflight through digital processing of any spectra obtained from a spectral survey type instrument having suitable spectral resolution. Thus the need for correlation spectrometry is limited to those special cases where insufficient time is available for complete spectral data gathering.

While the heterodyne techniques provide high spectral resolution, they are the most complicated of the instruments considered by the panel, and it is far from clear that such high resolution is needed for tropospheric sounding. However, the panel noted that detection of species having larger concentrations in the stratosphere than in the troposphere (e.g., ozone and nitric acid) may require such high spectral resolution to penetrate to the troposphere. Long integration times are necessary to achieve sufficient signal-to-noise ratios for detection of radiances emitted by tropospheric species. This in turn dictates a geostationary satellite as the platform for this technique. Such a platform, however, restricts the global coverage to approximately one-third of the globe, and consequently does not satisfy the scientific needs of global coverage with repeat measurements every 6 hours. The panel, however, recognized that coherent techniques enjoy a unique advantage over noncoherent

techniques; namely, coherent systems have inherently narrower IFOV's ($\Omega \simeq \lambda^2/A$) and consequently are able to maintain acceptable footprints even from geosynchronous altitudes. In general, it was felt that a great deal more analysis was required to establish fully the need for high spectral and spatial resolution and the desirability of employing a passive heterodyne system for tropospheric measurements.

At this point it is appropriate to comment on the long-term role of optical filter radiometers. These radiometers are relatively broadband and have proven useful in measuring vertical profiles of temperature and water vapor, total burdens of ozone, and aerosol optical thickness. In the long term it can be expected that such radiometers will continue to be used in a similar way for tropospheric research without requiring major changes or developments. For example, it was noted earlier that aerosol optical thickness data have been derived from current operational satellites having relatively broadband spectral channels, particularly when underlying surfaces have uniform reflectivities (e.g., oceans). Further algorithm development addressing varying surface reflectivity is warranted to make maximum use of available data. If, however, as noted previously, narrow-band spectral channels prove to be required to determine aerosol size distributions, then the Fabry-Perot filter radiometer may prove to be an alternative approach to conventional optical filter radiometers.

Table 11 was prepared to summarize the discussion of the roles of the various generic sensor types. The table is arranged in two groups, species-specific sensors and spectral survey sensors, and denotes limited projected roles for four species-specific techniques: correlation spectrometry, laser techniques, and optical and Fabry-Perot filter radiometers. Of the remaining passive techniques, one species-specific technique, gas filter radiometry, and two spectral survey techniques, interferometry and grating spectrometry, seem more promising. At this point it is not clear which approach (e.g., survey or specific) is more desirable, nor what the optimum spectral resolution is. Proven species-specific sensor concepts will likely find long-term use for selected measurements. It is clear, however, that a spectral survey instrument can provide sufficient data for measurements of several species, along with the temperature profile necessary for inversion of the radiative transfer equation to obtain gas profiles. The spectral scans, however, must be obtained over a time period consistent with the spatial resolution of measurement needs (e.g., 20 km), and the time available for a given scan is dependent upon the platform altitude. A suitable compromise to obtaining a full spectral survey from, say, 3.5 to 15 μm would be selective coverage of moderate bandwidth intervals (e.g., 100 cm^{-1}). As noted previously, the required spectral resolution has not been defined and will clearly depend upon the target species and spectral region. However, the system should be capable of a spectral resolution of at least 0.1 cm^{-1}. Either the interferometer or the grating technique offers the potential for meeting the general requirements just noted. In some respects, however, the grating system appears to offer the more desirable approach. It can be tailored as a hybrid species-specific and survey instrument covering selected wavelength bands with multiplexing advantage. Thus, while the complexity of survey instruments and the large data output inherent in such an approach were recognized, the panel leaned toward the survey approach because of its potential for detecting many gases (even some unsuspected ones) and providing clues as to the presence of interferents. Such an approach was felt to provide the broadest possible data base for program advancement as well as future instrument technique development, especially for future long-term monitoring.

As noted earlier, the gas filter correlation technique appears to be the most advanced technology for measuring tropospheric species. The current instrument, MAPS, can provide a weighted vertical profile of CO, and with improvements in

TABLE 11. PASSIVE REMOTE SENSING CONCEPTS

Generic sensor types	Potential long-term measurement roles		Heritage
Species-specific sensors:	**Long-term use of proven concepts for selected measurements:**		
Optical filter radiometer radiometer	Nadir view:	Profiles of temp., H_2O vapor,	SSH, HIRS
		Burden of ozone, aerosol optical thickness	TOMS, MSS, AVHRR
	Limb view:	Upper trop. profiles of aerosols and ozone	SAM II, SAGE, LIMS
Gas filter radiometer	Nadir view:	Two-layer measurements of CO, CH_4	MAPS
	Limb view:	Upper trop. feasibility TBD	HALOE
Fabry-Perot filter radiometer	Nadir view:	Limited long-term role	CLAES
	Limb view:	Limited long-term role	
Correlation grating spectrometer	Nadir view:	Limited long-term role	COSPEC
Laser heterodyne techniques	Nadir view:	Geosync. orbit { Limited role in penetrating	IHR
	Limb view:	Geosync. orbit { large strat. concentrations to trop. e.g., O_3, HNO_3	LHS
Spectral survey sensors:	**Preferred long-term concepts for max. measurement capability:**		
Grating spectrometer	Nadir view:	Many species and temp. profiles in 3.5- to 15-μm spectral range with spectral resolution of 0.1 cm^{-1} or better	SBUV
	Limb view:		SIRS B
Interferometer	Nadir view:		IRIS
	Limb view:		ATMOS

sensitivity can provide a two-level vertical profile measurement of both CO and CH_4 within the troposphere. At this point the gas filter correlation technology appears to be a strong candidate for tropospheric measurements of gases which can be contained within gas cells. Inherent in this technique is the need to understand the role of interferents so that, in the interpretation of the data, reasonable estimates can be made of the resulting effects and measurement accuracy. The panel, in spite of leaning toward spectral survey data, recommended continued development of the techniques of gas filter radiometry as a most promising way of obtaining data on the global distribution of important tropospheric trace species.

Sensing Strategies

The measurement concepts for tropospheric research considered thus far have primarily been nadir-viewing instruments; limb-viewing instruments are primarily used for stratospheric research. For several species of interest (e.g., O_3, HNO_3, NO, NO_2, and H_2O above 5 km), however, the concentrations are low enough that nadir sensing techniques may be very difficult to use. Further, for some species such as O_3 and HNO_3 a nadir-viewing instrument may not be capable of discriminating between the

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tropospheric concentration and the larger stratospheric concentration. The panel therefore stressed that limb viewing should not be discarded for tropospheric sensing without further study. Certainly, limb viewing in the troposphere will at times be limited by clouds to the upper troposphere.

Subsequent to this workshop, data from the AEM-SAGE satellite were made available indicating the probability of observations penetrating below the tropopause altitude to at least 6 km altitude, and also the probability of observations below 6 km. (See fig. 32.) These data were derived from January 1980 observations of solar occultation measurements by SAGE and were made available by the SAGE Science Team and Langley Research Center. These data are most encouraging, indicating that limb viewing of much of the free troposphere might be successful 50 percent of the time at midlatitudes. Several years worth of data are currently being studied to derive statistically valid observational probabilities representing various seasonal and meteorological conditions.

Both limb and nadir views are illustrated in figure 33. The relatively long path in the limb view provides an optical gain which is useful in sensing species that are either weakly absorbing or of low concentration or both. Compared to nadir viewing, limb-viewing radiance versus altitude weighting functions is typically quite sharp, with most of the radiance coming from the first few kilometers above the tangent altitude, thus providing extremely good vertical resolution. Therefore, the benefits of limb scanning may, through the long path geometry, provide a means of measuring the profiles of some of the more tenuous gases. It may also be possible to benefit from a measurement mode in which near-simultaneous nadir and limb viewing will permit the extraction of tropospheric data on species having large stratospheric concentrations. Instrumentation techniques and data inversion algorithms are highly developed for limb viewing because of extensive use in stratospheric research, and their applications for tropospheric measurements should be further investigated. The panel also noted that the long path advantage in studying the highly tenuous gases also results in aircraft and balloon platforms continuing to be viable approaches in tropospheric air quality research.

Response to Measurement and Mission Needs

The foregoing discussion has shown that passive remote sensing systems have the potential to address some of the measurement needs identified by the atmospheric chemists. Further, the experience with such systems allows us to capitalize on the advantages of these passive techniques for measurements of tropospheric species, even though it is acknowledged that additional studies are needed to resolve details of specific approaches.

Many of the species of interest in the chemistry of the troposphere are strong infrared absorbers. This fact alone provides encouragement that passive infrared techniques should prove fruitful. Yet for some of the species of interest, the concentrations are low enough that limb viewing is required in order to obtain an adequate amount of absorption. Satellite limb viewing at tropospheric altitudes presents a number of problems (e.g., probability that clouds will interfere with instrument field of view, off-axis rejection of radiation from disc, etc.) which may limit the technique to the upper troposphere. Off-axis rejection probably precludes use of emission techniques and suggests a solar occultation experiment using a high-resolution system such as ATMOS as a possible means of obtaining data on these species in the upper atmosphere.

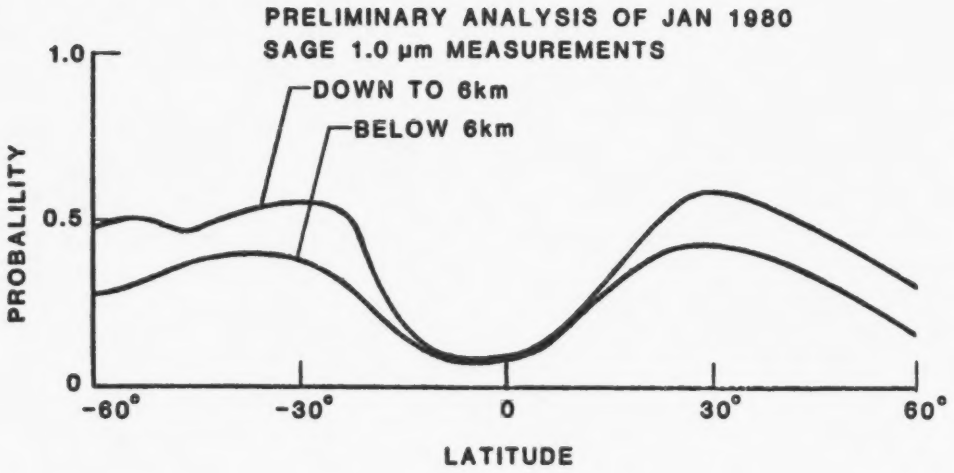

Figure 32.- Probability of limb-viewing measurements in the troposphere.

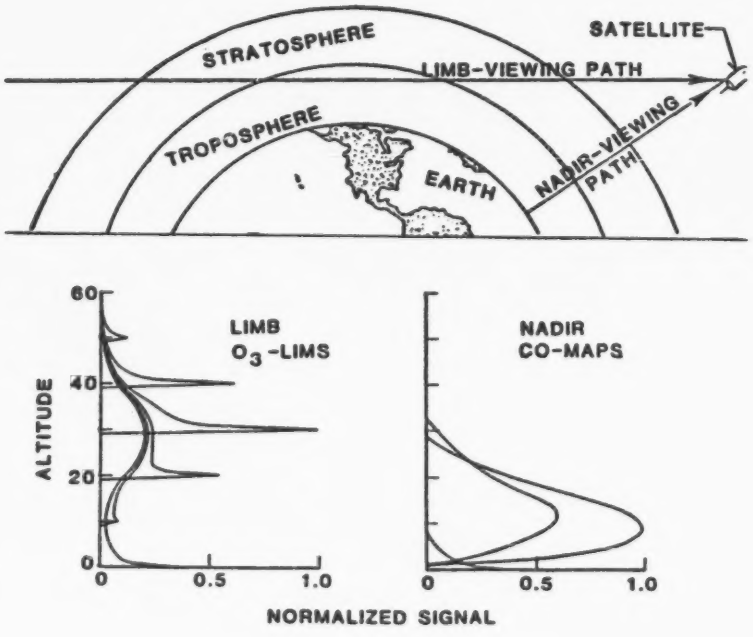

Figure 33.- Comparison of limb and nadir viewing.

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Several of the species of interest are present at high enough concentrations (H_2O, CH_4, CO, etc.) that the possibility of using nadir viewing to obtain data on these constituents appears reasonable. Since altitude information is needed for these constituents, spectral data are required which, due to the temperature dependence of the line strengths and the temperature and pressure dependence of the shape, will allow retrieval of altitude information from the data. The exact resolution and wavelength region scanned are parameters to be chosen as the satellite measurement objectives are better defined. For purposes of this discussion, a 0.1-cm^{-1} resolution instrument covering selected moderate bandwidth (100 cm^{-1}) intervals was considered as a possible system.

In trying to decide whether these systems would provide information of the type required by the atmospheric chemistry community, a number of questions arose which could not be answered within the time frame of the workshop. Some of these are:

1. How much will cloud interference degrade the performance of the solar occultation experiment and nadir-viewing instruments?

2. The nadir-viewing system noise is assumed to be due to the noise generated by the source (the Earth and its atmosphere). What are the magnitudes and spectral distribution of such noise? If noise becomes a significant limitation on the information that can be retrieved from the spectra, can it be reduced by using a staring mode of obtaining data?

3. Several of the species (e.g., HNO_3, O_3) have a large stratospheric concentration and a small tropospheric concentration. How well will either sensor retrieve data on the tropospheric concentration of the species?

These questions and other concerns are addressed in the recommendations made by the Sensor Systems Panel, which are presented in the section entitled Recommendations and Conclusions.

TECHNOLOGY THRUSTS FOR PASSIVE REMOTE SENSING

(SENSING TECHNOLOGY PANEL REPORT)

INTRODUCTION

The measurement needs identified for the troposphere include a number of constituents having mixing ratios which vary from 1 part in 10^6 to several parts in 10^{10} to 10^{11}. Most of the constituents are not uniformly mixed; this requires that the measurements provide some degree of vertical discrimination (at least two layers). The various generic sensing techniques that potentially have the sensitivity and discrimination necessary for this task, along with possible viewing geometries and associated sources, are shown in figure 34. The spectral radiances measured by the sensors are a function of the radiation source and the absorption and scattering characteristics of the atmospheric constituents in the optical path. The source may be either thermal emission of the atmosphere (in which case it is strongly dependent on atmospheric temperature profile) or solar energy in (1) a direct path occulted by the atmosphere (limb viewing only), (2) a double-transit path via reflection from the Earth's surface (nadir viewing only), or (3) multiple paths resulting from atmospheric scattering.

Limb-viewing measurements provide significant improvements in sensitivity by enhancing the optical depths available for low-concentration species and providing good vertical resolution due to the inherent atmospheric signal functions. Limb viewing of solar occultations will provide the maximum sensitivity for measurements of species having very low concentrations. The limb technique has poor horizontal resolution (on the order of several hundreds of kilometers) and consequently is very susceptible to cloud interference over this long optical path. However, measurements down to 10 km or less can be obtained in the absence of heavy cloud cover. Satisfactory operation of this type of instrument has been demonstrated, and no new, unique technology seems to be required for the limb-viewing measurement tasks reviewed by this panel. Further studies, however, are needed regarding limb sensor refinements and data usage, e.g., spectral resolution requirements for maximum penetration into the troposphere and utilization of simultaneous limb- and nadir-viewing measurements.

The nadir-viewing geometry has the advantage of good horizontal measurement resolution, and, therefore, the ability to look between the clouds to the lower atmospheric layers. It suffers, however, from the relatively short optical path through the atmosphere, limiting measurement sensitivity from atmospheric signal functions with poor vertical discrimination to only a few layers. In contrast to the limb-viewing sensor technology, if the nadir-pointing systems are to provide useful measurements of the free troposphere and boundary layer they will all require significantly new designs as well as components which are presently unavailable.

For the purposes of the workshop, measurement criteria were established as shown in table 12. Based on these criteria, a preliminary design requirements assessment was made, as documented in Appendix E. The intent of this appendix is to provide a more realistic look at the problem by being specific, yet without going to the point of making a final recommendation about mission selection. This approach (suggested by Dr. John A. Jamieson) provided a common viewpoint from which discussion began and to which previous experience could be related, and thus assisted in the discussion of those specific nadir-viewing techniques noted in figure 34. For example, table 13 presents some results from Appendix E relative to making measurements by scanning north and south from equatorial orbits. Since only orbital mechanics is involved,

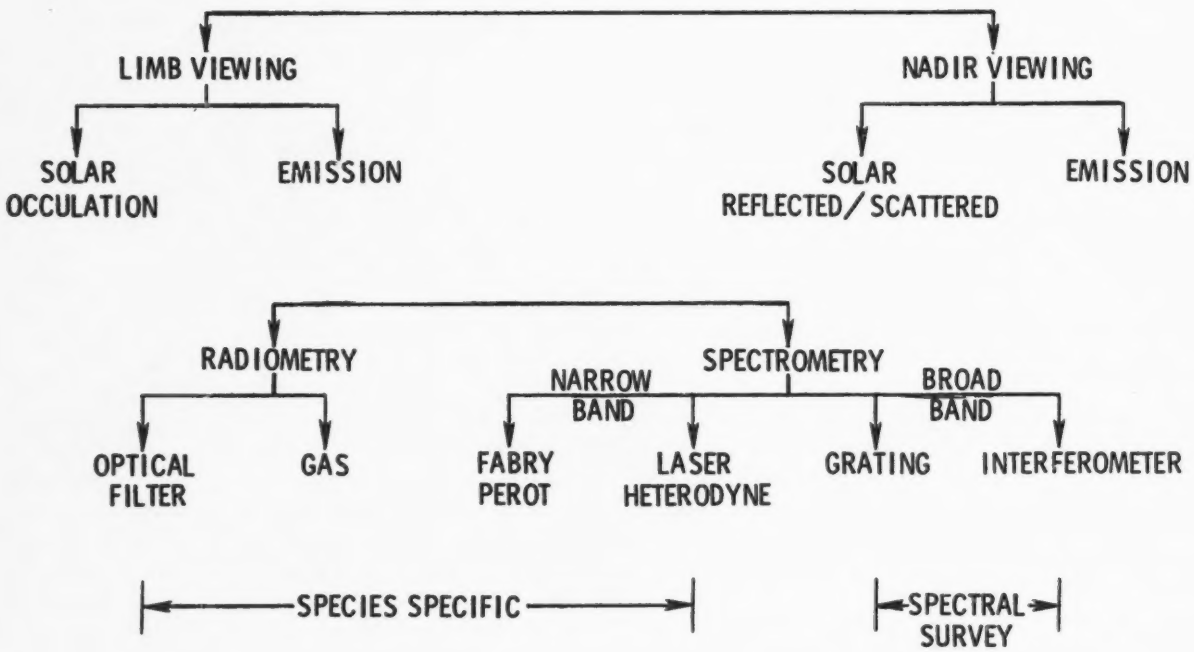

Figure 34.- Passive remote sensing tree showing generic techniques, viewing geometries, and associated sources.

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TABLE 12. MISSION MEASUREMENT CRITERIA

Parameter	Requirements
Constituents	CO NO H_2 CH_4 O_3 HNO_3
Wavelengths, μm	4.6 5.3 6.7 7.6 9.6 11.3
Spectral resolution	0.1 cm^{-1}
Radiometric measurement threshold	10^{-6} W/cm^2 sr cm^{-1}
Measurement footprint	20 km at nadir
Integration time	Satellite or scan system movement ≤20 km
Measurement coverage	±60° latitude

TABLE 13. TYPICAL DESIGN CONSTRAINTS
(based on table 12 and four equatorial orbits)

Parameter	Satellite altitude, km			
	40,000	8000	4000	400
IFOV, mrad	0.5	2.5	5.0	50
Max. latitude coverage, deg	±81	±64	±52	±20
(FOV/2) for ±60° latitude coverage, deg	8	26	NA	NA
Integration time, msec	-	29	23	60

the table applies no matter what instrumentation approach is used, and thus it represents constraints which influence the selection and detailed characteristics of the sensing instrumentation and its operation.

It was not possible to single out one obviously superior system for the nadir measurement requirement, although the advantages and disadvantages, from both a measurements and a technology viewpoint, were reviewed in as much detail as was allowed in the time available. In the following sections the systems shown in figure 34 are reviewed as they apply to nadir viewing, and their pros and cons and technology needs

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are tabulated. A summary of the panel's recommendations for further instrument analysis and for critical technology developments relating to the individual instrument approaches will be presented in a following section.

SPECIES-SPECIFIC SENSORS

Radiometry

Optical filter radiometers.- In the long term it is expected that optical filter radiometers will continue to be used in a way similar to that in which they are used today, without requiring major changes or developments. New techniques are needed, however, for the measurement of aerosol composition and physical properties. The challenge here is how to interpret and use the measured data. Since this is not an instrument technology problem, the Sensing Technology Panel did not address this in any detail.

Gas filter correlation (GFC) radiometry.- The gas filter radiometry approach is the passive measurement concept for remote tropospheric sensing which has the most flight experience to date. This technique has been flown in several aircraft experiments and on the OSTA 1 payload on STS 2 in November 1981, and it is scheduled for reflight on a later Shuttle mission during a different season. The advantages of this approach are that it has a low output data rate and requires relatively small postflight data processing. The instrument provides a high-energy throughput by utilizing spectral multiplexing across several constituent lines and by its basic optical design. The current design is relatively insensitive to the effects of variations in the observed background energy source, since each measurement is basically a "snapshot" of the instantaneous background. The instrument is relatively simple mechanically, requiring only a chopper and a rotating filter wheel for periodic inflight checks of gas response. The instrument also has a continuously active automatic gain control (AGC) feature, which minimizes the effects of short-term environmental variations. As currently implemented, the instrument obtains measurements along an orbital swath of width equal to the instantaneous field of view.

The disadvantage of the GFC instrument for future tropospheric work is primarily that its output represents a measurement of the constituent of interest based upon the atmospheric weighting function and provides no insight on the spectral information inherent in the observation. This is a limitation in two respects. First, no information is provided on the intrusion of unexpected atmospheric interferent lines which compromise the measurement. Second, the vertical discrimination (resolution) of the measurement is limited to the sharpness of the atmospheric signal function, which can be obtained by varying the amount and pressure of the constituent within the gas cell which serves as the instrument spectral filter. Since data reduction depends on knowledge of the stratospheric temperature profile, use of the GFC approach for autonomous measurements of temperature has generally been lacking in accuracy. Since the instrument is measurement-specific based on the gas filters installed and calibrated at the time of delivery, it does not provide in-orbit flexibility to change measurement objectives or conditions. The need to contain the gases of interest in known amounts and pressures within the gas filter cells for the total mission duration requires extreme care in selection of gas cell materials, fabrication, and filling procedures. Currently the gas-cell development status is adequate for most gases of interest; however, further work will be required on the generation and containment of ozone.

In order to develop the GFC approach for global measurements of the troposphere, the instrument should be modified by use of linear detector arrays to operate as a "push-broom scanner," providing a much wider swath of independent 20-km footprint measurements for each constituent. These arrays should allow integration times of 20 to 100 milliseconds, should have a large dynamic range with good linearity, and should achieve specific detectivities (D^*s) exceeding 10^{11} with good uniformity of response both between elements and across individual elements. To optimize the performance of the GFC approach, optical elements, filters, and coatings are needed which have very uniform characteristics across their surfaces and which are also uniform and/or stable as a function of incident optical beam angle.

In order to include ozone as a measured constituent, techniques for the generation and containment of this gas in known amounts and pressures over long time periods must be developed as part of the research and development program. For other potential measurands, e.g., NO and HNO_3, the first order of business is an evaluation of their potential signal-to-noise ratios versus data user needs.

To summarize, extension of the GFC for global measurements of the recommended constituents requires that technology development be done on linear detector arrays in the 2.0- to 12-μm wavelength range, that coating and fabrication technology for optical elements be improved to provide better spatial uniformity, and that gas cell technology for the generation and containment of ozone be developed. It is also recommended that instrument systems studies be performed to explore the technological implications of implementing the GFC as a push-broom scanner to meet global measurement requirements.

Narrow-Band Spectrometry

This category of instrument technology includes Fabry-Perot solid etalons and passive laser heterodyne spectrometers. Both instrument techniques are currently under study and development for measurement of stratospheric trace constituents in solar occultation and limb emission geometries from spaceborne and airborne platforms. In this section of the report, comments are offered strictly for their applications in viewing IR thermal emission of the Earth-atmosphere system. When comparing Fabry-Perot and laser heterodyne spectroscopy with other spectrally discriminating remote sensing technology (i.e., interferometers/spectrometers), the Fabry-Perot and heterodyne technologies share limited spectral advantages over selected ranges in the infrared. Spectral resolving power of the Fabry-Perot is at best comparable with Michelson interferometers. The resolving power of the heterodyne technology can be 1 to 2 orders of magnitude greater than interferometry, but it is generally limited to detecting emission lines over a spectral range of 1.0 cm^{-1} with existing technology.

The technology assessment for narrow-band spectrometry was based upon:

1. The potential need for higher vertical resolution to discriminate between the stratospheric (Doppler-broadened) and tropospheric (pressure-broadened) contributions to the thermal emission at the top of the atmosphere

2. The potential that the very high resolution available in the case of heterodyne technology provides finer vertical resolution within the troposphere itself than do the broader band spectrometric and gas filter technologies; it is important to recognize that for those atmospheric

species with relatively sharply peaked profiles in the stratosphere (i.e., O_3, HNO_3 . . .), as opposed to more uniformly mixed gases, the very high resolution technology offers the potential (possibly in a unique way) to discriminate tropospheric from stratospheric thermal emission using a nadir-looking sounder at the top of the atmosphere

In the case of the Fabry-Perot, spectral resolving power is comparable at best to Michelson interferometry with reduced spectral coverage (i.e., limited to measurements of a small number of spectral lines). However, the Fabry-Perot offers a distinct advantage in mechanical simplicity, especially for long-duration free-flyer missions.

In the case of heterodyne technology, the ultimate noise limitation is the shot noise induced by the laser local oscillator, but a limitation of this very high resolution sounder for thermal emission is the low source temperature (220 to 300 K) compared to the solar temperature (~5000 K) for occultation measurements. This leads to a reduced signal-to-noise ratio with this narrow-band sounder, which may require integration times only marginally suited for low Earth orbits but adequate for geosynchronous altitudes. A common consensus of the Sensing Technology Panel was that more detailed simulation studies must be performed in order to define the role of narrow-band spectrometry in satellite sounding of the troposphere.

Fabry-Perot spectrometer.- The main advantages of the Fabry-Perot etalon spectrometer are ruggedness and mechanical simplicity. It shares with the Michelson interferometer the advantage of high throughput relative to a grating spectrometer. However, background photons arriving at the detectors are confined, for a cold etalon, to the narrow spectral bandpass of the measurement. This should lessen requirements for reducing stray radiation by optics cooling and telescope baffling. Temperature fluctuations of an etalon can cause severe calibration problems; however, if it is used in a cryogenic mode, as anticipated because of sensitivity requirements, etalon temperatures should be highly controlled. It is anticipated that multiple etalons will be required to measure even a small number of trace gases, and this will lead to a significant total optical port heat load in a nadir-viewing instrument, with a consequent impact upon the cooling requirement.

It is estimated that, in a tropospheric application, the resolving power of the etalons will be 2-1/2 times higher than that of the CLAES instrument designed for the stratosphere. With this spectral resolution (0.1 cm^{-1}) it is inconceivable that tilt tuning will be permissible because of signal-to-noise considerations. Thus the etalon instrument's spectral coverage will be limited to a relatively small number of discrete 100 cm^{-1} channels. Of course the data rate of such an instrument is much lower than a full-coverage spectrometer. The development of higher resolution etalons at new wavelength regions will probably be required for a tropospheric experiment, and this may mean improving optical coatings of etalons at longer wavelengths.

Laser heterodyne spectrometry.- The major advantage of laser heterodyne spectroscopy in tropospheric sounding (thermal emission) is the very high spectral resolution for potential discrimination between stratospheric and tropospheric line emissions, and potential provision of the ability to obtain tropospheric emissions for those gases with sharply peaked concentration profiles in the stratosphere (i.e., O_3, HNO_3 . . .). For fairly well mixed gases, heterodyne techniques may increase vertical discrimination within the troposphere itself, if the radiative transfer processes of the Earth-atmosphere inherently contain the information. The inherently narrow field of view of heterodyne technology may provide the added capabilities of

enhanced viewing through patchy cloud cover and high horizontal resolution near strong frontal systems. Limitations of this technology include a limited tuning range and a narrow bandpass currently constrained by the tunable range of local oscillators and photomixer technology. Useable signal-to-noise ratios for this technology are available at the expense of integration time, which appears, at a minimum, to be compatible for geosynchronous altitudes and possibly for other Earth orbital missions.

Technology needs in the case of heterodyne techniques include continued development of widely tunable laser local oscillators in the 2- to 20-μm spectroscopic range and development of heterodyne detector arrays to provide an imaging capability coupled to the high spectral resolution and narrow instantaneous-field-of-view capability. However, the development of heterodyne array technology may require parallel technology development in signal processing and signal conditioning of the IF (intermediate frequency) signals from the photomixer array. Development of integrated circuit technology for heterodyne techniques to reduce weight, power, and volume also represents a high-technology thrust which, although not a current need for tropospheric sounding, represents an enhancing technology for both passive and active heterodyne techniques with a variety of applications in planetary atmospheres and remote sensing of the Earth's atmosphere.

SPECTRAL SURVEY SENSORS (BROADBAND SPECTROMETRY)

Broadband spectrometry techniques are plausible candidates for emission spectrometry in either nadir-looking or limb-looking sensing and for solar occulatation in limb viewing. In order to measure tropospheric species from space, the technique used must have sufficient spectral resolution (on the order of 0.03 to 0.3 cm^{-1}) to sense pressure-broadened tropospheric spectra in the presence of stratospheric spectra. This section of the report will compare a class of techniques using large gratings combined with linear arrays of detectors and a class of techniques using interferometers. However, before making this comparison it may be useful to discuss the advantages and disadvantages of broadband spectrometry as compared to narrow-band spectrometry or gas filter radiometry.

Broadband spectrometry can yield detailed resolved spectra over broad bands of wavenumbers. This capability would permit surveys of spectra for unexpected species populations or effects as well as predicted species. Detailed spectra permit detailed interpretation to determine interference between species and between the same species at different altitudes. Broadband spectrometry also facilitates the critical examination of quantitative inferences and a degree of diagnosis of instrumental distortions or experimetal difficulties. Spectra offer a potential for interpretation of interferences by aerosols and clouds, particularly if broadband spectrometry is augmented by simultaneous boresighted imagery. This capability may be particularly important in the presence of thin high clouds. Detailed examination of spectra for pressure broadening can permit a degree of vertical discrimination.

On the other hand, spectra resolved to a fraction of a wavenumber contain a great deal of detail, which must be measured quantitatively to a high degree of precision. In this application, where measurements are to be made several times per day on some millions of spatially resolved patches, the data rates are very high and the total number of data words gathered will be very great. Consequently, data processing will require very large computational power intensively applied. Depending on the extent to which this data processing is done on board, very high telemetry channel capacity will be required. To derive the greatest benefit from the detailed

data, the unprocessed data should be returned for ground interpretation from all those frames which are substantially uncontaminated. Therefore a large part of the burden may fall upon communication and ground-processing facilities.

The sensing instruments for broadband spectroscopy are themselves complex, precise, and relatively delicate, and require complex high-quality optics. The intrinsic capability to take data to a resolution of a fraction of a wavenumber places fundamental limits on the size of field of view that can be used (Jamieson, 1976); thus the system must scan over the total field. The instruments are required to be in precise alignment throughout their mission, and they require detailed accurate calibration and monitoring in use to verify that the calibrations have not changed.

The rate of data acquisition requires that information bandwidths of each detector channel be relatively high, which in turn requires that means be provided to make the equipment highly responsive so that signals shall be greater than noise. The spectral resolution requires that optical path differences within the equipment be tens of centimeters (Jamieson, 1976). These two requirements together dictate that the optics be large.

The information content available in the data from broadband spectrometry may be sufficient to allow the sensors to be adapted through on-board processing, at least to the extent of rejecting unwarranted data to reduce the burden on telemetry. It is perhaps possible to develop these sensors as "smart sensors" to select and edit data and conceivably to control the sensing itself to improve the scientific yield from applied resources and effort.

Grating Spectrometry

One class of techniques for broadband spectrometry uses large gratings combined with arrays of infrared detectors. (Instruments which use gratings with a single detector or a detector for each gas species would be too slow for this application because the high spectral resolution mandates use of a narrow entrance slit and sensing at a large number of angles into which the spectral intervals are coded). Since several species are to be measured whose spectra extend over more than an octave in frequency (e.g., 3.5 to 15 μm), several gratings are required (or a compound grating with several differently blazed regions). Since a resolution of approximately 0.1 cm^{-1} is required, each grating must be on the order of several tens of centimeters wide. Since each species is to be measured over a wavenumber band containing approximately 1000 spectral resolution intervals, a combination of detectors and grating angles of the same order is required. In the discussions, the Sensing Technology Panel supposed that the grating might be held fixed and arrays containing on the order of 1000 detectors could be used. This approach should yield an instrument of maximum sensitivity at a cost of establishing and maintaining a correspondingly large number of calibrations.

This strategy would yield an instrument which, although large and complex, would be fixed internally, so that problems with reliability due to spectral scanning would be avoided. The whole instrument would be scanned for spatial coverage. The key elements of such a sensor would include large aperture foreoptics, a spectrometer with a large multiblaze grating, linear arrays with 1000 elements per spectrum, supporting structure and electronics, a mechanical chopper, a cross-track scanning mirror, a grating adjustment mechanism, and a cooling system to control the temperature of the foreoptics, the spectrometer, and the detector arrays.

Requirements identified for technology development included arrays of about 1000 infrared detectors at wavelengths from 3.5 to 15 μm, and large gratings. The detector arrays will probably call for special characteristics of uniformity, linearity, and dynamic range which may not be found in detectors developed for other applications. For example, much of the current work on linear detector arrays is directed toward very-high-speed response, whereas detectors in this application would operate with integration times of, perhaps, up to 30 msec. Technology advancements for gratings include the use of multiple gratings or a compound grating with several differently blazed regions. Both arrays and grating require cooling to temperatures of 70 K or lower. A technology development program should include (1) development of a suitable sensor model, (2) a large (e.g., 1 m) multiblaze grating, (3) line arrays peaked at the appropriate cutoff wavelengths, (4) programmable 1000-element spectral correlators, and (5) development of a demonstration model. Questions which should be addressed early in the program include:

1. Is there a significant degradation in information retrieval when a few detectors are missing, as in the case where submodules are butted together to achieve the 1 × 1000 array?

2. How flexible is the 100-wavenumber bandwidth?

3. What performance can be achieved if no new detector arrays are developed?

4. What are the cooling requirements, and are any new technologies required?

Interferometers

A second class of techniques for broadband spectrometry is the modulated (Fourier transform) interferometers. These instruments utilize phase retarders which allow two beams of light to interfere at a number of path differences. In this application the spectral resolution on the order of 0.1 cm^{-1} would require that the phase retarder be driven from zero path difference to about 10 cm. The incident spectra are coded by this means to a modulation at the output of one or more detectors which can be processed by conventional electronics. The modulation takes the form of a Fourier transform of the incident spectrum. For this application it may be desirable to use one detector for each spectral subband to be sensed (perhaps on the order of 10 detectors).

This class of instruments is intrinsically sensitive because an entrance slit is not required and each spectral frequency is measured for the total spectral observation time. The field of view of the instrument is limited by the path difference required, so that the sensor must be scanned to achieve spatial coverage. Scanning the path difference of the instrument requires an accurate linear translation device, which requires excellent engineering for linearity, regularity, maintenance of alignment (including on-board alignment monitoring and control), and long life.

The type of Fourier transform spectrometer most commonly used is a Michelson beam-splitting interferometer. The cylindrical symmetry of this device is not easily adapted to use with multiple fields of view. A suggested alternative for this application is a multiaperture interferometer supported by a grating for preselection of bands. The Fourier transform processing contains an implicit assumption that the spectrum being measured does not change during the spectral scan. In this application the spectra could be degraded or contaminated if the background were to change during a spectral scan. The extent and importance of this effect require further

investigation. Another recommendation is that further development be done on multi-field high-resolution interferometers for use in space if it is NASA's intention to utilize this technology.

SUMMARY OF TECHNOLOGY NEEDS

It is apparent from the two panel discussions that the choice of the optimum system for nadir measurements is far from clear. On one hand, the trade-off between minimum complexity and maximum data yield has not been determined. On the other hand, there has not been sufficient study and analysis to determine how well a specific system will operate even if all the technology becomes available. Obviously, detailed system studies are needed for the candidate approaches. Of the six basic types of sensors shown in the remote sensing tree (fig. 34), only one, the gas filter radiometer, has had space flight experience in nadir viewing for measuring gases other than H_2O and O_3. The MAPS sensor on STS 2 measured the total burden of CO. The task is to extend the number of species that can be measured by species-specific sensors such as the gas filter radiometer, and to complement them with sensors that survey a complete spectral region. Table 14 compares the generic types of nadir-viewing sensors by summarizing their advantages and disadvantages. Also listed are the associated technology needs. Certain technology thrusts deserve emphasis since they are needed regardless of the sensing system selected. These thrusts are (1) detector arrays, (2) cryogenic cooling (of sensors and optics), (3) sophisticated optical elements, and (4) data processing as an integral part of the sensor. A final item, calibration techniques and equipment, should be added to this list of needed technology thrusts even though it is not explicitly mentioned in table 14. The workshop reiterated the calibration needs delineated in the 1979 Flight Technology Workshop (National Aeronautics and Space Administration, 1979).

Generally, the workshop participants felt that over the long term the preferred strategy would be broadband spectrometry in thermal emission, since all the species in a spectral region with sufficient signal could be measured day or night. More monitoring flexibility is available regarding species; e.g., new species of interest and interferents would be measured, and there is the potential for good vertical resolution. There is no doubt, however, that broadband spectrometry is complex and must handle much data. The detailed requirements of the user, the evaluation of the instrument designer, and the relative costs should be the three determining factors for implementation of a system and for the development and support of the appropriate new technologies. The Sensing Technology Panel's recomendations regarding critical technology developmental thrusts are summarized in the next section.

TABLE 14. COMPARISON OF NADIR-SENSING TECHNIQUES

Type	Advantages	Disadvantages	Technology needs
Gas filter radiometry			
All types	Low data rate Minimal data reduction High throughput (spectral and angular)	No detailed spectra Limited temperature profiles Test cells limited Species fixed after launch	Gas filter test cells Linear, high-dynamic-range detectors Highly uniform optical elements
Broadband spectrometry			
All types	Detailed spectral data Survey data Vertical discrimination	High data rate and processing Complex calibration Complex optical train Requires long stability Angle scan	On-board smart processing Cryogenics/cooling
Grating (with linear array)	Simple mechanism	Needs line array for sensitivity Large area gratings	10^3 element arrays Large gratings
Interferometer	High throughput	Background fluctuations Lifetime of high-scan-rate reflector	Mitigation of background fluctuations Multiaperture, multiband interferometer In-flight alignment verification
Narrow-band spectrometry			
Laser heterodyne spectroscopy	High spectral resolution for vertical discrimination	Limited tuning range	Tunable lasers and heterodyne arrays
Fabry-Perot	Simplicity	Limited tuning range Temperature stability	Improved coatings at long wavelengths

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RECOMMENDATIONS AND CONCLUSIONS

SENSOR SYSTEMS PANEL RECOMMENDATIONS

Following are the conclusions and recommendations from a systems point of view for passive remote sensing of tropospheric constituents:

1. Passive remote systems exhibit promise and should be developed for two-layer measurement of some of the more abundant tropospheric species (e.g., O_3, CO, CH_4, CO_2, HNO_3, H_2O, NO, etc.).

2. A measurement scenario consisting of a combination of nadir viewing and solar occultation should be considered for measurement of gases such as O_3 and HNO_3. Measurement of these gases in the troposphere presents a unique challenge in that well over 90 percent of the total burden of the gas resides in the stratosphere.

3. For multilayer (i.e., more than two) measurements of a wide range of species, a nadir-viewing instrument capable of obtaining continuous spectra in the 3- to 15-μm spectral region with a spectral resolution of less than 0.1 cm^{-1} is desired.

4. Gas filter radiometer instruments (e.g., MAPS and HALOE) should be developed concurrently with a scanning instrument. (See previous recommendation.) Such systems may provide near-term two-layer tropospheric measurements of gases such as CO and CH_4 with only modest improvements in system performance. For gases such as O_3, HNO_3, and NO, major problems may be encountered with the gas cell technology and resolving more than one atmospheric layer.

5. Further development of aerosol retrieval algorithms is required for obtaining aerosol thickness and size distributions on a global scale. While the technology currently exists for obtaining aerosol information over water, additional channels extending from the visible to near IR would be desirable for future measurements.

6. Reassess the prospect of initiating (and possibly initiate) a feasibility study to determine if polarization measurements of scattered solar radiation can yield the refractive index (i.e., composition) of aerosols.

7. Existing spectrally scanning radiometers (e.g., interferometers) and/or gas filter systems should be employed from balloon and Shuttle platforms to study the effects of instrument noise and background fluctuations on inversion techniques. Short-term nadir-viewing Shuttle missions should be coordinated with existing solar occultation missions to study the feasibility of utilizing simultaneous occultation and nadir-viewing data.

8. Feasibility studies for both gas filter and spectrally scanning instruments should be initiated to study (a) the extent to which nadir-viewing systems can obtain profiles of two or more layers within the troposphere, (b) the accuracy requirements on molecular line parameters, meteorological parameters (i.e., temperature and pressure), radiance data, and background effects, and (c) the extent to which solar scattering can be used to obtain lower level tropospheric data.

SENSING TECHNOLOGY PANEL RECOMMENDATIONS

The technology needs presented earlier are restated in table 15 as critical needs and are recommended as technology developmental thrusts for elements of several passive sensing techniques for tropospheric research. In one sense, this table indicates the needs once a system is chosen. In a larger sense, the technology requirements and their apparent difficulty and cost should be a critical part of the instrument evaluation studies. Certain technology thrusts, however, are needed regardless of the sensing system choice. Examples from table 14 are (1) detector arrays, (2) cryogenic cooling (of sensors and optics), (3) sophisticated optical elements, and (4) data processing as an integral part of the sensor. Although not explicit in table 14, calibration techniques and equipment should be added to the list of needed technology thrusts. The workshop reiterated calibration needs delineated in the 1979 Flight Technology Workshop (National Aeronautics and Space Administration, 1979). In response to the continuing need for more sensitive and accurate measurements over the full globe for long periods of time, producing great volumes of data, the workshop participants felt that the application of technology advances in these five areas would yield the greatest benefit in passive remote sensing of the troposphere.

TABLE 15. TECHNOLOGY THRUSTS

Sensor	Technology needs
Gas filter radiometry	
All types:	Gas filter test cells Linear, high dynamic range detectors Highly uniform optical elements
Broadband spectrometry	
All types:	Onboard smart processing Cryogenics/cooling
Grating type:	10^3 element arrays Large gratings
Interferometer:	Mitigation of background fluctuations Multiaperture, multiband interferometer In-flight alignment verification
Narrow-band spectrometry	
Laser heterodyne type:	Tunable lasers and heterodyne arrays
Fabry-Perot:	Improved coatings at long wavelengths

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CONCLUDING REMARKS

A modest but meaningful and challenging role has been defined for passive remote sensors in the Tropospheric Air Quality Program. It deals with determining the chemistry and transport of the more abundant trace species with intermediate lifetimes. It prescribes global-scale, multilayer measurements using both limb- and nadir-viewing techniques with both species-specific and spectral survey sensors. Since spectral survey sensors have the potential for detecting both "new" species of interest and interferents, these sensors could play a valuable complementary role in relation to active sensors.

Regarding technology developments, the application of limb-viewing sensors to the troposphere should be relatively easy because of the rich science and technology heritage being provided by the stratospheric program. Development activities, therefore, should concentrate on the nadir-viewing sensors. The recommended technology thrusts are in the areas of (1) applying maturing technologies such as detector arrays and sensor-integral data processing to both sensor-specific and spectral scanning sensors, and (2) performing the detailed systems studies and flight evaluation tests on the candidate approaches.

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APPENDIX A

ATTENDEES

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APPENDIX B

RESPONSES TO PREWORKSHOP QUESTIONS

INTRODUCTION

To assist in the preparation for the workshop each panel member was asked to consider four questions and to share the responses with the other participants. The results of this preworkshop activity are presented here. Generally, the text consists of verbatim responses; however, they have been organized under each question and hence do not necessarily represent one individual's complete response in sequence.

QUESTION 1

What are the most serious weaknesses of today's passive remote sensor systems and the individual technology elements (optics, detectors, mechanisms, filters, etc.)?

Sensor Systems

- The major challenge in passive remote sensing of atmospheric trace constituents, particularly in the troposphere, is that of obtaining sufficient sensitivity along with the required specificity. Sensitivity requirements demand that the signal bandpass and optical throughput be as large as possible, while specificity requires the highest possible spectral resolving power. These generally contradictory requirements are difficult to reconcile. Standard spectrometers provide either a large bandpass or high spectral resolving power, but not both. Correlation instruments are a promising approach for some species measurements. Another approach that appears potentially useful in attacking this problem is the Fabry-Perot etalon. This approach could require technological developments in three areas; these are discussed in the response to Question 4.

- Today's remote sensor systems suffer from the same weaknesses that have always plagued them: lack of sensitivity, selectivity, and/or excessive data transmission. Each particular measurement technique suffers from one or more of these weaknesses.

- While the detection capabilities of sensor systems can be improved with increased detector sensitivity, better spectral filtering, and the like, I don't think these are the serious weaknesses of today's passive remote sensor systems. I think the real weaknesses in current passive remote sensor technology are in the areas of system calibration, verification, and control. The quantities inferred from a remote sensing measurement are frequently limited by system calibration. To have confidence in the measurements, the sensing system's performance must also be verified during the course of the experiment. Finally, in dealing with a complex sensing system, the capability to accurately control it (pointing, sampling rate, wavelength scanning, frequency sweeping, etc.) can be the primary factor in obtaining useful data.

- Inability to measure altitude (vertical) distribution of gaseous constituents to desired resolution

- Inability to measure all atmospheric and background parameters which affect accuracy of algorithm (e.g., temperature profile, background temperature, or emissivity) within a sensor system

- Long-term stability of hardware required to work with low-SNR signals from tenuous constituents (ppb)

- Inadequate sensitivity for airborne or global measurements of many important species (e.g., NO, NO_2, NH_3, OH, HO_2)

- Difficult to obtain the desired vertical resolution

- Many of the present sensor systems are dependent on the solar radiation, which precludes diurnal measurements

- In many cases the spectral resolution is not optimum for minimizing interference from other species

- At the present time there is no satellite or aircraft sensor dedicated to the measurement of tropospheric aerosols; measurements of the aerosol optical thickness have been made with the Landsat MSS, the NOAA 6 AVHRR, and the GOES VISSR. The weaknesses of existing techniques are as follows:

  - No vertical resolution is possible
  - Absolute calibration of sensors needs improvement
  - Coverage is not optimum; Landsat is every 18 days, and even though NOAA 6 is daily, its equator crossing is 0730 and limits observations to the summer months
  - The GOES has continuous coverage of some areas but has poor sensitivity to aerosol changes due to its six-bit data system
  - Aerosol scattering depends on so many parameters that several must be assumed to be known in order to interpret observations
  - Accurate measurements over land not yet demonstrated

- There are too few monitoring (surveillance) measuring systems which measure data over a number of years so that diurnal, seasonal, and long-term trends can be assessed. There is also a need for both local and broad geographic measurements.

Technology Elements

- Among the technology elements, the infrared detectors have several drawbacks: the need for cooling, the relative difficulty and expense involved in making imaging system, the inadequate frequency response for some applications, and the susceptibility to damage.

- Of the individual elements, detector weaknesses are sensitivity at high operating temperature, uniformity, and stability of response. The requirements of narrow filters with sharp skirts require extension of today's technology. Most small filters are produced by cutting a larger filter into small chips causing edge effects and chips in the coating and thus degraded characteristics.

- Sensitivity of optical elements and filters to environment and to input radiance conditions, e.g., polarization
- Area responsitivity nonuniformities and variations in responsivity temperature coefficients associated with detectors
- Lack of stable inflight calibration sources, particularly in $\lambda < 5$ μm region
- Thermal stability of detector coolers
- Long-term cryogenic cooling means
- Calibration means - both facilities and on-board calibrations; narrow-band long-wavelength calibrations are hardly available
- Polarizers are only marginally available in the infrared.
- Measurements sometimes have inadequate off-axis rejection. The quality of baffling of the telescopes is less than it should be.

QUESTION 2

Are there other passive techniques, or variations thereon, that show promise for troposphere sensing (e.g., photopolarimetry, microwave, or millimeter techniques)? What technologies may now be limiting the advancement of such techniques?

- I believe there may be some very useful passive remote sensing techniques for tropospheric sensing which rely on measurements of scattered and transmitted solar radiation (both visible and near-IR). The SAGE, SAM II and SBUV satellite programs appear to have been quite successful in stratospheric sensing. It would appear that some of these approaches, including sky intensity, polarization, and hemispheric flux measurements, could be employed from aircraft platforms for tropospheric sensing. Technological limitations which may be a factor in attempting to implement these approaches in tropospheric sensing include aircraft positioning limitations, sensor pointing limitations, and ruggedization of sensitive spectral scanning equipment to maintain required accuracy on board an aircraft platform.
- A combination of gas correlation and dispersive techniques could be used to improve selectivity of the standard gas-correlation technique. This improvement may be limited by present grating spectral separations capability.
- A multidetector mosaic could improve geographic coverage while maintaining the required small IFOV and not require a dual-axis scanning system. A uniform response mosaic and a readout technique providing maximum information with minimum data handling will be required for this improvement.
- Possibilities exist for infrared polarization radiometry using emerging new wire grid polarizers and for rare-event observation using charge-coupled device arrays and microprocessor logic.

QUESTION 3

Does the remote sensing perspective provided by various platforms (geosynchronous satellites, low-Earth-orbit satellites, aircraft) and the available viewing geometries (nadir, off-nadir, limb) result in special capabilities or limitations of certain sensing techniques?

- The remote sensing perspective provided by various platforms most definitely results in special capabilities and/or limitations of certain sensing techniques. For example, an aircraft platform offers the unique advantages of (1) providing unambiguous height information via flying vertical profiles, (2) providing a platform for either upward- or downward-looking measurement approaches, (3) providing a platform which can retrace over a given area "on command" rather than waiting for another satellite pass, and (4) providing greater spatial resolution by virtue of the medium being sensed (troposphere) being closer to the sensing platform. By the same token, satellite systems offer the advantage of readily covering large areas of the atmosphere, which is not feasible even with fleets of aircraft. The "integrated" measurement (both vertical and horizontal integration) provided from a satellite is effectively impossible to achieve with a reasonable number of aircraft.

- Desired spatial resolutions from geosynchronous altitudes pose extreme noise-equivalent radiance (NEN) requirements on sensors, particularly for nadir viewing.

- Aerosol measurements need to be made from above the scattering atmosphere; this means that satellites or high-flying aircraft, such as the U2, are required.

- The geosynchronous orbit is useful for continuous monitoring of pollution episodes. The Sun-synchronous orbit is good for global coverage; a noon equator crossing would be preferred for aerosol measurement.

QUESTION 4

Are there potential advances in (1) fundamental properties of materials; (2) infrared, millimeter wave, or microwave devices and components such as optics, filters, detectors; (3) electronics; (4) data processing, especially when it is an integral part of the sensor; or (5) sensor support subsystems such as cryogenic coolers and precision pointing or attitude determination systems that may significantly impact the development of interferometers, spectroradiometers, heterodyne radiometers, gas filter radiometers, or any other passive sensing technique for the measurement of tropospheric gaseous trace species, aerosols, or related atmospheric state variables?

Detector Arrays

- Landsat follow-on missions beyond thematic mapper will probably be done using detector arrays in the pushbroom mode rather than single detectors in mechanically scanned systems. The next generation system, which is being pursued by Goddard Space Flight Center, will use line arrays in the visible and near IR out to 2.5 μm. Beyond the line array approach, Jet Propulsion Laboratory is pursuing the development of area arrays that can operate out to

2.5 μm in an imaging spectrometer mode. (One axis of the array would be spatial and the other axis spectral, thus allowing selection of spectral channels by ground command.)

- The DOD continues to push array technology primarily in the infrared atmospheric windows. Unfortunately, some of the interesting tropospheric data lie on the edges of these windows, and the edges are not of interest to the DOD. Also, the devices are generally designed as broadband detectors, and many of them have serious drawbacks when applied to narrow-band, low-level spectrometry.

- Work is being done on InSb photodiode line arrays (5.4-μm cutoff) for future planetary reflectance mapping spectrometers. The value of these detectors for tropospheric work is questionable considering the present state of the art in coolers. The cooler problem is probably tractable, but development rate is dollar-limited at a low level.

- To take advantage of IR detector arrays, considerable work is required to develop appropriate optical and electrical means for on-board calibration, sensitivity correction, data compression, and data quality criteria.

- Infrared detector arrays, e.g. platinum silicide, HgCdTe

- Considerable progress has been made in charge-coupled device (CCD) technology in recent years. Texas Instruments is now making a device for space telescope application with 800 × 800 pixels over 1.5 cm^2 that images from 0.12 to 1.1 μm. Advancements are now under way in this technology that will improve the performance in the 0.3- to 0.4-μm range. Sensitivities better than 10 photons per picture element are being achieved. To take advantage of these devices in very low contrast imagery that might be useful in mapping some gases and aerosols, work needs to be done to develop optical systems with very low scattering while viewing a diffuse object of large solid angle.

- Potential advances in detector mosaics and data processing could improve gas filter radiometers.

Optics

- The NASA Office of Space and Terrestrial Applications (OSTA) is supporting a study of a large-aperture imaging spectrometer with high spatial resolution and modest spectral resolution (1:200) for use as a spectrally flexible Landsat follow-on. This approach could be modified to increase spectral resolution at the expense of spatial resolution for spectral mapping applications. The study is considering various options for dispersion, including a classical grating approach and integrated optics spectral splitters.

- Quasi-optical antennas are under development for millimeter/submillimeter work, and will be used on the UARS microwave limb sounder.

Filters, Gratings, Etalons

- Spectral filter research and development appears to be supported only by system users. This is an area that could better support future systems if some preproject work could be supported.

- Tuneable filters appear to be feasible as system components, given early enough definition of requirements. Again, the viability of project usage hinges on preproject development.

- Improvement in filters and dispersive gratings could impact the development of a hybrid system.

- Development of larger (3") solid etalons, with their throughput advantage over air gap etalons, has been accomplished by some research groups, and scenarios for their use in passive trace species measurements have been proposed. An important development which is being pursued is a solid etalon that can be used at cryogenic temperatures. Even small cryogenic etalons can achieve high sensitivity in the IR through reduction of instrument photon noise, although their use will require significant advances in cooling capacities due to optical port loading alone.

- The use of large etalons could perhaps be facilitated by using infrared detector arrays in place of single detector systems. Such an array has been suggested for use in an advanced Michelson interferometer temperature sounder.

- Polarizers, particularly infrared

Additional Responses

- Precision pointing ahead of and behind orbital path would enable the scattering layer to be viewed from different angles to possibly get more information on aerosol parameters.

- To increase the vertical and horizontal resolution of tropospheric temperature and moisture profiles significantly beyond currently operational systems appears to require a considerable effort in optics development and sensor technology. Such an effort is being funded by NASA but a new-generation sensor is at least a decade away in present plans.

- In summary, solid Fabry-Perot etalon technology, cryogenics (closed-cycle refrigerators with primary cooling capacities on the order of 1 W at 100 K), and infrared detector array development have been singled out as key technological areas for the problem of passive remote sensing of tropospheric trace species.

- Advances in electronics, data processing approaches, and sensor support and control systems could all significantly impact the development of passive tropospheric remote sensing systems. In particular, advances in the aforementioned areas should improve upon system calibration, verification, and control. As noted in the response to Question 1, these three items are of critical importance in the sucessful implementation of a remote sensing system.

APPENDIX C

SELECTED TOPICAL REFERENCES

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APPENDIX D

ACRONYMS AND ABBREVIATIONS

AEM	Atmospheric Explorer Mission
ATMOS	Atmospheric Trace Molecules Observed by Spectroscopy
AVHRR	Advanced Very High Resolution Radiometer
CCD	Charge-coupled device
CLAES	Cryogenic Limb Array Etalon Spectrometer
COSPEC	Correlation Spectrometer
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
GAMETAG	Global Atmospheric Measurements Experiment on Tropospheric Aerosols and Gases
GOES	Geostationary Operational Environmental Satellite
HALOE	Halogen Occultation Experiment
HIRS	High-resolution Infrared Radiation Sounder
IFOV	Instantaneous field of view
IHR	Infrared Heterodyne Radiometer
IR	Infrared
IRIS	Infrared Interferometer Spectrometer
ITPR	Infrared Temperature Profile Radiometer
LHS	Laser Heterodyne Spectrometer
LIMS	Limb Infrared Monitor of the Stratosphere
MAPS	Measurement of Air Pollution from Satellites
MSS	Multispectral Scanner
NCAR	National Center for Atmospheric Research
NEN	Noise-equivalent radiance
NEP	Noise-equivalent power
NESN	Noise-equivalent spectral radiance
NOAA	National Oceanic and Atmospheric Administration
OAST	Office of Aeronautics and Space Technology (NASA)
OSSA	Office of Space Science and Applications (NASA)
OSTA	Office of Space and Terrestrial Applications (NASA)
PMR	Pressure modulator radiometer
SAGE	Stratospheric Aerosol and Gas Experiment
SAM II	Stratospheric Aerosol Measurement II
SAMS	Stratospheric and Mesospheric Sounder
SBUV	Solar Backscatter Ultraviolet
SIRS	Satellite Infrared Spectrometer
SNR	Signal-to-noise ratio
SSH	Special Sensor H
STS	Space Transportation System
THIR	Temperature Humidity Infrared Radiometer
TIROS	Operational satellite series
TOMS	Total Ozone Measurement System
UARS	Upper Atmospheric Research Satellite
UV	Ultraviolet
VISSR	Visible, Infrared Spin Scan Radiometer
VTPR	Vertical Temperature Profile Radiometer
WMO	World Meterological Organization

APPENDIX E

PRELIMINARY DESIGN REQUIREMENTS ASSESSMENT FOR SENSING TECHNOLOGY PANEL

INTRODUCTION

The Sensor Systems Panel reported that the recommended thrust for the measurement of tropospheric species of interest to the scientific community should emphasize the survey approach wherein detailed spectral information would be gathered. Only this approach is considered herein. The material which follows was intended to provide a "systems look", which would first allow a "quick-look" assessment of feasibility, and also assist the Sensing Technology Panel in its concerns for technology needs. The haste with which this concept was implemented at the workshop necessitated many assumptions, very few second thoughts or iterations, and a truly "back-of-the-envelope" or "zero-order" assessment.

MISSION DESCRIPTION

Characteristics of the measurement mission are as follows:

- Measure minor atmospheric species (H_2O, CO, CH_4, NO, O_3) and aerosols in free troposphere and boundary layer troposphere
- Identify major sources and sinks
- Measure "globally" ($\pm 60^{\circ}$ lat?)
- Resolve regions to approximately 20 km
- Identify diurnal and seasonal effects
- Reasonable, affordable
- Launch in about 15 years
- Precursor aircraft sampling

There is a need to measure minor atmospheric species, such as the ones listed, plus aerosols. The concern is primarily with measurements of radiance and other data required to interpret the results, such as the temperature structure of the atmosphere. The atmospheric regions of concern are the free troposphere and the boundary layer; consequently, there is a need to relate our measurements to several layers, with two layers as a minimum.

The identification of major sources and sinks and their global distributions is of prime interest. Although the term global is used, $\pm 60^{\circ}$ latitude coverage is interpreted as probably adequate. It may be difficult to cover the polar caps, and most probably the major chemical activities governing these trace species occur in the broad latitude band $\pm 60^{\circ}$. Also, 20 km is a reasonable spatial resolution. There should also be the capability to look at diurnal and seasonal effects. The mission should certainly be reasonably affordable, and perhaps launch can be considered in about 15 years. In the interim, defined technology needs can be addressed and the satellite mission can benefit from precursor missions using aircraft methodologies.

SOME CHOICES

Such a mission statement begins to set some specifications. Some of these choices are:

- Type of orbit - equatorial:

  Altitude
  Circular/elliptical

- Sensing strategy:

  Solar occultation
  Emission spectroscopy
  Solar scattering

- Type of sensor:

  Interferometer
  Grating
  Radiometer
  Correlation sensor

The first choice is what type of orbit to have. An equatorial orbit seems desirable for scanning to both north and south latitudes, since much of the desired geographic regions would be accessible. Then, should there be a circular orbit, or can an ellipitical orbit serve any purpose? There does not appear to be any strong reason for choosing Sun-synchronous orbits, although it is conceivable that some situations (aerosols) may be influenced by particular solar scattering angle situations.

Regarding the choice of sensing strategy, the most frequently selected strategy is emission spectroscopy. With regard to the type of sensor, it is suggested that there be a combination grating and interferometer, for some reasons which shall be discussed subsequently. There was some disagreement on this point, but for this discussion this will be the focus. Some of the consequences of this choice are presented subsequently, and available trade-offs between sensor resources are discussed by Jamieson (1976).

Some spectral concerns to be noted are as follows:

- Species: CO, NO, H_2O, CH_4, O_3, HNO_3
- Center wavelength, μm: 3.5, 5.3, 6.7, 7.6, 9.6, 12
- Aerosols: visible and near-infrared
- Multiple channels rather than continuous coverage
- Resolution: ~0.03 to 0.3 cm^{-1}
- Path difference: 30 to 3 cm
- Excellent resolution: to see pressure-broadened wings

- Grating: grating - etalon

- Modified stellar interferometer

Presented first are some specific trace constituents and an approximate center wavelength for each. If aerosols are included, some portion of the visible spectrum must be included as well. Altogether there is a very broad spectral range to be considered. It is suggested that we perhaps want to do this with about six or eight channels, each of which is about 100 wavenumbers wide, and each channel is looked at with perhaps a 0.1-wavenumber resolution. In other words, measurement of the whole spectral band from 3 to 12 μm would not be attempted. One would deliberately pick appropriate 100-cm^{-1} regions and resolve each to, say, 0.1 cm^{-1}. Principal considerations here are revisit time, integration time, and the bandwidth of the detector. All of the spectral data for the total range are not requested because of the "tyranny of the numbers", but excellent resolution is needed (e.g., to see the pressure-broadened wings) to invert to at least two different layers.

So, as indicated, a grating from which we select six or eight 100-cm^{-1} intervals, followed by a modified stellar interferometer, will provide a workable approach. It is not known whether a scheme such as this has been considered before, but it seems to be a way to accomplish our task. Multiple detectors are envisioned here, though not CCD detectors. A linear array of detectors for each spectral region, all in the same interferometer, is a possibility. Spatial scanning, or positioning, of the instrument will be required to provide off-nadir (latitude) coverage. (Other means of making measurements of the trace gases, such as gas filter correlation radiometry, are not considered here because spectral details cannot be obtained.)

GEOGRAPHIC COVERAGE

The next topic has to do with the geographic coverage and some consequences of the choice of orbital altitude. In table E1, four equatorial altitude alternatives are noted: synchronous, which is roughly 40,000 km altitude, and 8000, 4000, and 400 km. A number of criteria are listed on the left. Figure E1 may aid in viewing these geometric considerations. The spatial resolution is given in milliradians for the 20-km surface resolution element. Then, how much aperture diameter is needed to produce the needed sensitivity? Rough calculations indicate needs of about 1-1/3 m at synchronous equatorial altitude, 0.6 m at 8000 km, 0.45 m at 4000 km, and about 15 cm at 400 km to do the job. By coverage we mean the latitude range visible from the various altitudes, e.g., ±80° from geosynchronous altitude. The half field of view required to provide coverage to ±60° latitude from equatorial orbit is also given. The dwell time is the time for the satellite ground track to advance by one resolution element (20 km) . The number of individual resolution elements during a "scan" between ±60° latitude is tabulated next as snapshots per FOV (±60° latitude). If this "scan" is accomplished during the dwell time, then a so-called integration time is the time available for detecting or reading out the radiance from each resolution element. Of the cases selected, the intermediate (boxed off) tabulation is the most reasonable, since the medium- and low-altitude orbits do not provide ±60° latitude coverage and the complications of the synchronous altitude seem unwarranted.

The notes represent concerns expressed by the Sensing Technology Panel. Certainly the capability to launch into equatorial orbits from the Space Shuttle will exist, and the selection of such an orbit does allow the geographic area of interest to be viewed. The concern over optics size is, of course, a real concern, but one that this cursory look could not adequately address. Finally, sensitivity concerns led to the discussion in the following section.

TABLE E1. GEOGRAPHIC COVERAGE CONDITIONS (EQUATORIAL ORBITS)[a]

Parameter	Altitude			
	Synchronous (40,000 km)	Medium (8000 km)	Medium (4000 km)	Low (400 km)
Orbital period, hr	24	4.77	2.92	1.54
IFOV, mrad	0.5	2.5	5	50
Aperture diameter, m	1.35	0.60	0.45	0.15
Latitude coverage, max., deg	±81	±64	±52	±20
FOV/2 for ±60° latitude, deg	8	26	NA	NA
Dwell time, sec	-	11	6	3
Snapshots per FOV (±60° lat.)	560	367	-	-
Integration time, msec	-	29	-	-

[a] Notes: Supplementary launch vehicle
Can concentrate on selected geometry
Very large field may require multiple or heroic optics
Sensitivity will be difficult to obtain

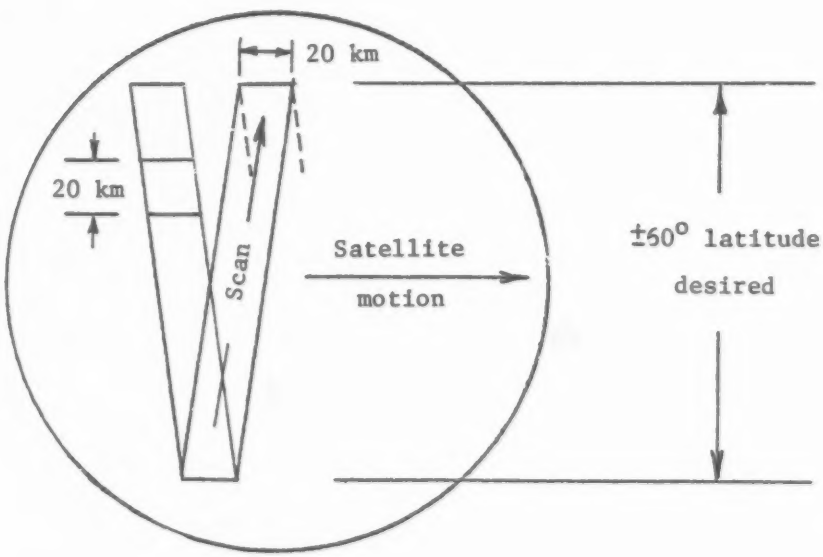

Figure E1.- Viewing geometry.

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SENSITIVITY

Some considerations of radiometric sensitivity are as follows:

Requirement to measure features or radiometric size: $N = 10^{-6}$ W/cm^2 sr cm^{-1}

Throughput: $A = (20 \text{ km})^2 = 4 \times 10^{12}$ cm^2

$$\Omega = \frac{1 \text{ m}}{8000 \text{ km}} = \frac{10^{-12}}{64} \text{ sr}$$

Feature spectral width: $\Delta\nu = 0.1$ cm^{-1}

Feature power: $P = 10^{-6} (4 \times 10^{12}) \left(\frac{10^{-12}}{64}\right) (10^{-1}) = 6.25 \times 10^{-9}$ W

BLIP specific detectivity for detectors at 60° FOV and 295 K:

Specific Detectivity	Band (μm)			
	3.5	7	10	12
D^*_{BLIP} (60°, 295 K)	$2(10)^{12}$	$2(10)^{11}$	10^{11}	10^{11}
D^*_{BLIP} (cold filter)	$2(10)^{13}$	$2(10)^{12}$	10^{12}	10^{12}
D* (practical)	10^{13}	10^{12}	$5(10)^{11}$	$5(10)^{11}$

where the effect of a 100-cm^{-1} cold band has been estimated as 10× and the departure from BLIP has been estimated as 1/2.

Noise-equivalent power:

Detector side = 0.5 cm × 0.5 cm

Bandwidth $\simeq \frac{\nu}{\Delta\nu} \cdot \frac{1}{\Delta t} = 3.5(10)^4$ Hz

$$\text{NEP} = \frac{\sqrt{\Delta d}\ \sqrt{\Delta f}}{D^*} = \frac{10^2}{D^*}$$

Parameter	Band (μm)			
	3.5	7	10	15
NEP (W)	10^{-11}	10^{-10}	$2(10)^{-10}$	$2(10)^{-10}$
Signal/detector noise	625	63	31	31

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The order of magnitude of the spectral radiance to be measured is assumed to be 10^{-6} W/cm^2 sr cm^{-1}. The resolution area is 20 km on a side and the solid angle is defined by assuming a 1-m aperture. As noted previously, the spectral width for each measurement is 0.1 cm. This results in a feature power at the 8000-km altitude of $6.25(10)^{-9}$ W.

Consider now using a cooled filter over the detectors when estimating the resulting specific detectivity, D*, for the four spectral bands (3.5, 7, 10, and 12 μm). Cooling was estimated to improve the D* by a factor of 10, and the departure from BLIP was estimated as one-half. The practical D* values which result are 10^{13}, 10^{12}, $5(10)^{11}$, and $5(10)^{11}$, respectively, for the four bands.

The noise-equivalent power (NEP) was considered next. The detector size was based on an f/2 system to provide the IFOV defined by the resolution desired (20 km) at the 8000-km altitude. The derived NEPs are tabulated and the resulting signal-to-noise (detector) ratios are shown.

This very cursory analysis is not proof of feasibility by any means. There are factors that have been omitted; e.g., optical efficiency, the quantum effiency of the detectors, off-axis rejection, and many others. It does, however, appear encouraging.

CONCLUDING REMARKS

Many aspects of the suggested approach are not considered herein. A system is not designed, or even completely specified. Operational aspects and their influences on design specifications (e.g., pointing and stabilization) and other mission requirements have not been studied.

A brief summary of the system suggested here would include the following points:

- Sensor should have small IFOV to permit high spectral resolution
- A reflective system should be used to accept all bands from 3.5 to 15 μm
- A grating should be used to "preselect" 100-cm^{-1} bands at each species
- An interferometer should be used to scan each band to 0.1 cm^{-1}
- An array of detectors should be used, one for each band

The suggested system is a grating followed by a stellar interferometer. The sensor should have a small IFOV to accomplish the desired high spectral resolution. The primary optics should be reflective to accept the large midinfrared band from 3.5 to 15 μm. The 15-μm region has been included in this summary since its use for atmospheric temperature profiling is imperative for data reduction and analysis. The grating would provide the spectra for the preselection of six to eight 100-cm^{-1} bands centered near the trace species of interest. The interferometer would be used to scan each band to the desired 0.1-cm^{-1} resolution. A linear array of detectors should be used, one for each band. In this way, one would be applying resources to gather the desired information and not wasting time and other resources gathering data where there is not useful information.

REFERENCE

Jamieson, John A., Passive infrared sensors: Limitations on performance, Appl. Opt., 15, 891-909, 1976.

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15. Supplementary Notes

16. Abstract

The National Aeronautics and Space Administration sponsored a Tropospheric Passive Remote Sensing Workshop in Virginia Beach, Virginia, July 20-23, 1981. Approximately 20 scientists and technologists participated. The purpose of the workshop was to define the long-range role of passive remote sensors in tropospheric research and identify the technology advances necessary to implement that role. Measurement and mission needs for the study of the chemistry and related dynamics of the lower atmosphere were addressed. A promising role of passive remote sensors is in making measurements of multigaseous species (e.g., O_3, CO, CH_4, HNO_3) and of aerosol thickness and size distribution. The sensing strategy consists of a combination of nadir-viewing and limb-viewing techniques making IR measurements for the gaseous species and visible and near-IR measurements for aerosols. Spectral resolution for the nadir measurements of 0.1 cm^{-1} or better is desired. Technology advances focus on the nadir-viewing techniques for gaseous species. Both spectral survey instruments and fixed-spectra gas filter radiometers should be developed concurrently. Balloon- and Shuttle-borne experiments should be performed to study the effects of instrument noise and background fluctuations on data inversion techniques and to determine the utility of simultaneously obtained limb-viewing and nadir-viewing data.

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